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(54) **OXIDE ETCH SELECTIVITY ENHANCEMENT**

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(56) **References Cited**

U.S. PATENT DOCUMENTS

2,369,620 A 2/1945 Sullivan et al.  
3,451,840 A 6/1969 Hough  
3,537,474 A 11/1970 Rohrer  
3,756,511 A 9/1973 Shinroku

(Continued)

FOREIGN PATENT DOCUMENTS

EP 1675160 A1 6/2006  
JP S59-126778 A 7/1984

(Continued)

OTHER PUBLICATIONS

Manual No. TQMA72E1. "Bayard-Alpert Pirani Gauge FRG-730: Short Operating Instructions" Mar. 2012. Agilent Technologies, Lexington, MA 02421, USA. pp. 1-45.

(Continued)

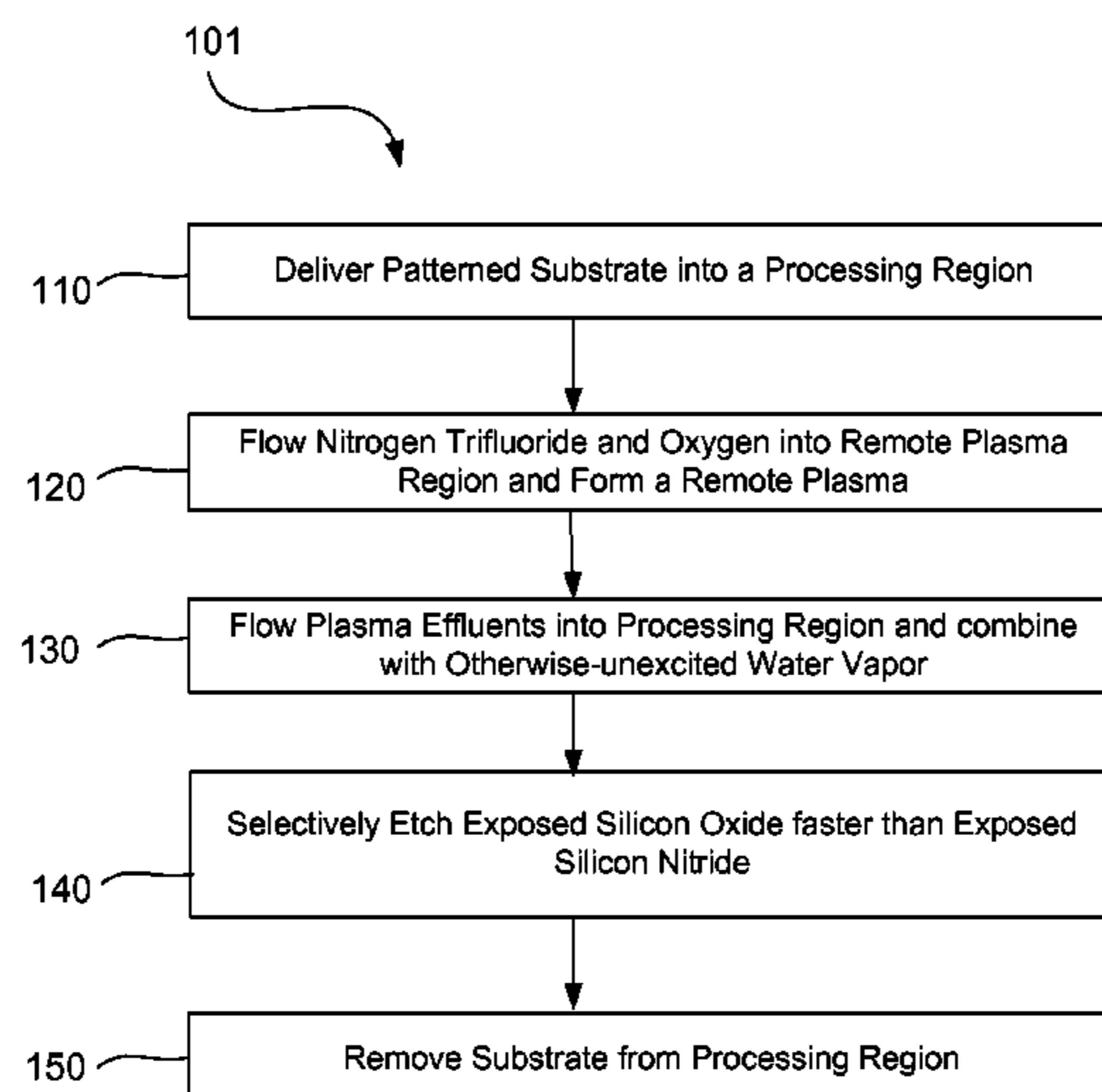
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(57) **ABSTRACT**

A method of etching exposed silicon oxide on patterned heterogeneous structures is described and includes a gas phase etch using plasma effluents formed in a remote plasma. The remote plasma excites a fluorine-containing precursor in combination with an oxygen-containing precursor. Plasma effluents within the remote plasma are flowed into a substrate processing region where the plasma effluents combine with water vapor or an alcohol. The combination react with the patterned heterogeneous structures to remove an exposed silicon oxide portion faster than an exposed silicon nitride portion. The inclusion of the oxygen-containing precursor may suppress the silicon nitride etch rate and result in unprecedented silicon oxide etch selectivity.

**12 Claims, 6 Drawing Sheets**



(56)

## References Cited

## U.S. PATENT DOCUMENTS

3,937,857 A	2/1976	Brummett et al.	5,215,787 A	6/1993	Homma
3,969,077 A	7/1976	Hill	5,228,501 A	7/1993	Tepman et al.
4,006,047 A	2/1977	Brummett et al.	5,231,690 A	7/1993	Soma et al.
4,209,357 A	6/1980	Gorin et al.	5,235,139 A	8/1993	Bengston et al.
4,214,946 A	7/1980	Forget et al.	5,238,499 A	8/1993	van de Ven et al.
4,232,060 A	11/1980	Mallory, Jr.	5,240,497 A	8/1993	Shacham et al.
4,234,628 A	11/1980	DuRose	5,248,371 A	9/1993	Maher et al.
4,265,943 A	5/1981	Goldstein et al.	5,248,527 A	9/1993	Uchida et al.
4,341,592 A	7/1982	Shortes et al.	5,252,178 A	10/1993	Moslehi
4,361,418 A	11/1982	Tscheppe	5,266,157 A	11/1993	Kadomura
4,361,441 A	11/1982	Tylko	5,269,881 A	12/1993	Sekiya
4,364,803 A	12/1982	Nidola et al.	5,270,125 A	12/1993	America et al.
4,368,223 A	1/1983	Kobayashi et al.	5,271,972 A	12/1993	Kwok et al.
4,374,698 A	2/1983	Sanders et al.	5,275,977 A	1/1994	Otsubo et al.
4,397,812 A	8/1983	Mallory, Jr.	5,277,750 A	1/1994	Frank
4,468,413 A	8/1984	Bachmann	5,279,669 A	1/1994	Lee
4,565,601 A	1/1986	Kakehi et al.	5,279,865 A	1/1994	Chebi et al.
4,579,618 A	4/1986	Celestino et al.	5,288,518 A	2/1994	Homma
4,585,920 A	4/1986	Hoog et al.	5,290,382 A	3/1994	Zarowin et al.
4,610,775 A	9/1986	Phifer	5,292,370 A	3/1994	Tsai et al.
4,625,678 A	12/1986	Shioya et al.	5,300,463 A	4/1994	Cathey et al.
4,632,857 A	12/1986	Mallory, Jr.	5,302,233 A	4/1994	Kim et al.
4,656,052 A	4/1987	Satou et al.	5,306,530 A	4/1994	Strongin et al.
4,656,076 A	4/1987	Vetanen et al.	5,314,724 A	5/1994	Tsukune et al.
4,690,746 A	9/1987	McInerney et al.	5,319,247 A	6/1994	Matsuura
4,715,937 A	12/1987	Moslehi et al.	5,326,427 A	7/1994	Jerbic
4,749,440 A	6/1988	Blackwood et al.	5,328,558 A	7/1994	Kawamura et al.
4,753,898 A	6/1988	Parrillo et al.	5,328,810 A	7/1994	Lowrey et al.
4,786,360 A	11/1988	Cote et al.	5,334,552 A	8/1994	Homma
4,793,897 A	12/1988	Dunfield et al.	5,345,999 A	9/1994	Hosokawa
4,807,016 A	2/1989	Douglas	5,352,636 A	10/1994	Beinglass
4,810,520 A	3/1989	Wu	5,356,478 A	10/1994	Chen et al.
4,816,638 A	3/1989	Ukai et al.	5,362,526 A	11/1994	Wang et al.
4,820,377 A	4/1989	Davis et al.	5,368,897 A	11/1994	Kurihara et al.
4,828,649 A	5/1989	Davis	5,380,560 A	1/1995	Kaja et al.
4,838,990 A	6/1989	Jucha et al.	5,382,311 A	1/1995	Ishikawa et al.
4,851,370 A	7/1989	Doklan et al.	5,384,284 A	1/1995	Doan et al.
4,857,140 A	8/1989	Loewenstein	5,385,763 A	1/1995	Okano et al.
4,865,685 A	9/1989	Palmour	5,399,237 A	3/1995	Keswick et al.
4,868,071 A	9/1989	Walsh et al.	5,399,529 A	3/1995	Homma
4,872,947 A	10/1989	Wang et al.	5,403,434 A	4/1995	Moslehi
4,878,994 A	11/1989	Jucha et al.	5,413,670 A	5/1995	Langan et al.
4,886,570 A	12/1989	Davis et al.	5,413,967 A	5/1995	Matsuda et al.
4,892,753 A	1/1990	Wang et al.	5,415,890 A	5/1995	Kloiber et al.
4,894,352 A	1/1990	Lane et al.	5,416,048 A	5/1995	Blalock et al.
4,904,341 A	2/1990	Blaugher et al.	5,420,075 A	5/1995	Homma et al.
4,904,621 A	2/1990	Loewenstein et al.	5,429,995 A	7/1995	Nishiyama et al.
4,913,929 A	4/1990	Moslehi et al.	5,439,553 A	8/1995	Grant et al.
4,946,903 A	8/1990	Gardella et al.	5,451,259 A	9/1995	Krogh
4,951,601 A	8/1990	Maydan et al.	5,464,499 A	11/1995	Moslehi
4,960,488 A	10/1990	Law et al.	5,468,342 A	11/1995	Nulty et al.
4,980,018 A	12/1990	Mu et al.	5,474,589 A	12/1995	Ohga et al.
4,981,551 A	1/1991	Palmour	5,478,403 A	12/1995	Shinagawa et al.
4,985,372 A	1/1991	Narita et al.	5,478,462 A	12/1995	Walsh
4,991,542 A	2/1991	Kohmura et al.	5,483,920 A	1/1996	Pryor
4,992,136 A	2/1991	Tachi et al.	5,500,249 A	3/1996	Telford et al.
4,994,404 A	2/1991	Sheng et al.	5,505,816 A	4/1996	Barnes et al.
5,000,113 A	3/1991	Wang et al.	5,510,216 A	4/1996	Calabrese et al.
5,006,192 A	4/1991	Deguchi	5,516,367 A	5/1996	Lei et al.
5,013,691 A	5/1991	Lory et al.	5,518,962 A	5/1996	Murao
5,028,565 A	7/1991	Chang	5,531,835 A	7/1996	Fodor et al.
5,030,319 A	7/1991	Nishino et al.	5,534,070 A	7/1996	Okamura et al.
5,038,713 A	8/1991	Kawakami et al.	5,536,360 A	7/1996	Nguyen et al.
5,045,244 A	9/1991	Marlett	5,549,780 A	8/1996	Koinuma et al.
5,061,838 A	10/1991	Lane et al.	5,558,717 A	9/1996	Zhao et al.
5,083,030 A	1/1992	Stavov	5,560,779 A	10/1996	Knowles et al.
5,089,441 A	2/1992	Moslehi	5,563,105 A	10/1996	Dobuzinsky et al.
5,089,442 A	2/1992	Olmer	5,567,243 A	10/1996	Foster et al.
5,147,692 A	9/1992	Bengston	5,571,576 A	11/1996	Qian et al.
5,156,881 A	10/1992	Okano et al.	5,578,130 A	11/1996	Hayashi et al.
5,180,435 A	1/1993	Markunas et al.	5,578,161 A	11/1996	Auda
5,186,718 A	2/1993	Tepman et al.	5,580,421 A	12/1996	Hiatt et al.
5,188,706 A	2/1993	Hori et al.	5,591,269 A	1/1997	Arami et al.
5,198,034 A	3/1993	deBoer et al.	5,599,740 A	2/1997	Jang et al.
5,203,911 A	4/1993	Sricharoenchaikit et al.	5,614,055 A	3/1997	Fairbairn et al.
			5,616,518 A	4/1997	Foo et al.
			5,624,582 A	4/1997	Cain
			5,626,922 A	5/1997	Miyanaga et al.
			5,628,829 A	5/1997	Foster et al.



(56)

## References Cited

## U.S. PATENT DOCUMENTS

5,635,086 A	6/1997	Warren, Jr.	5,944,049 A	8/1999	Beyer et al.
5,645,645 A	7/1997	Zhang et al.	5,944,902 A	8/1999	Redeker et al.
5,648,125 A	7/1997	Cane	5,948,702 A	9/1999	Rotondaro
5,648,175 A	7/1997	Russell et al.	5,951,601 A	9/1999	Lesinski et al.
5,656,093 A	8/1997	Burkhart et al.	5,951,776 A	9/1999	Selyutin et al.
5,661,093 A	8/1997	Ravi et al.	5,951,896 A	9/1999	Mahawili
5,674,787 A	10/1997	Zhao et al.	5,953,591 A	9/1999	Ishihara et al.
5,676,758 A	10/1997	Hasgawa et al.	5,953,635 A	9/1999	Andideh
5,679,606 A	10/1997	Wang et al.	5,968,610 A	10/1999	Liu et al.
5,685,946 A	11/1997	Fathauer et al.	5,969,422 A	10/1999	Ting et al.
5,688,331 A	11/1997	Aruga et al.	5,976,327 A	11/1999	Tanaka
5,695,810 A	12/1997	Dubin et al.	5,990,000 A	11/1999	Hong et al.
5,712,185 A	1/1998	Tsai et al.	5,990,013 A	11/1999	Berenguer et al.
5,716,500 A	2/1998	Bardos et al.	5,993,916 A	11/1999	Zhao et al.
5,716,506 A	2/1998	Maclay et al.	5,997,962 A	12/1999	Ogasawara et al.
5,719,085 A	2/1998	Moon et al.	6,004,884 A	12/1999	Abraham
5,733,816 A	3/1998	Iyer et al.	6,007,635 A	12/1999	Mahawill
5,747,373 A	5/1998	Yu	6,007,785 A	12/1999	Liou
5,753,886 A	5/1998	Iwamura et al.	6,010,962 A	1/2000	Liu et al.
5,755,859 A	5/1998	Brusic et al.	6,013,191 A	1/2000	Nasser-Faili et al.
5,756,400 A	5/1998	Ye et al.	6,013,584 A	1/2000	M'Saad
5,756,402 A	5/1998	Jimbo et al.	6,015,724 A	1/2000	Yamazaki et al.
5,772,770 A	6/1998	Suda et al.	6,015,747 A	1/2000	Lopatin et al.
5,781,693 A	7/1998	Ballance et al.	6,017,414 A	1/2000	Koemtzopoulos et al.
5,786,276 A	7/1998	Brooks et al.	6,020,271 A	2/2000	Yanagida
5,789,300 A	8/1998	Fulford	6,030,666 A	2/2000	Lam et al.
5,800,686 A	9/1998	Littau et al.	6,030,881 A	2/2000	Papasouliotis et al.
5,804,259 A	9/1998	Robles	6,035,101 A	3/2000	Sajoto et al.
5,812,403 A	9/1998	Fong et al.	6,037,018 A	3/2000	Jang et al.
5,814,238 A	9/1998	Ashby et al.	6,037,266 A	3/2000	Tao et al.
5,814,365 A	9/1998	Mahawili	6,039,851 A	3/2000	Iyer
5,820,723 A	10/1998	Benjamin et al.	6,053,982 A	4/2000	Halpin et al.
5,824,599 A	10/1998	Schacham-Diamand et al.	6,059,643 A	5/2000	Hu et al.
5,830,805 A	11/1998	Schacham-Diamand et al.	6,063,683 A	5/2000	Wu et al.
5,843,538 A	12/1998	Ehrsam et al.	6,063,712 A	5/2000	Gilton et al.
5,843,847 A	12/1998	Pu et al.	6,065,424 A	5/2000	Shacham-Diamand et al.
5,844,195 A	12/1998	Fairbairn et al.	6,072,147 A	6/2000	Koshiishi
5,846,332 A	12/1998	Zhao et al.	6,072,227 A	6/2000	Yau et al.
5,846,373 A	12/1998	Pirkle et al.	6,074,512 A	6/2000	Collins et al.
5,846,375 A	12/1998	Gilchrist et al.	6,077,780 A	6/2000	Dubin
5,846,598 A	12/1998	Semkow et al.	6,080,529 A	6/2000	Ye et al.
5,849,639 A	12/1998	Molloy et al.	6,081,414 A	6/2000	Flanigan et al.
5,850,105 A	12/1998	Dawson et al.	6,083,344 A	7/2000	Hanawa et al.
5,855,681 A	1/1999	Maydan et al.	6,083,844 A	7/2000	Bui-Le et al.
5,856,240 A	1/1999	Sinha et al.	6,086,677 A	7/2000	Umotoy et al.
5,858,876 A	1/1999	Chew	6,087,278 A	7/2000	Kim et al.
5,865,896 A	2/1999	Nowak	6,090,212 A	7/2000	Mahawill
5,866,483 A	2/1999	Shiau et al.	6,093,457 A	7/2000	Okumura
5,872,052 A	2/1999	Iyer	6,093,594 A	7/2000	Yeap et al.
5,872,058 A	2/1999	Van Cleemput et al.	6,099,697 A	8/2000	Hausmann
5,882,424 A	3/1999	Taylor et al.	6,107,199 A	8/2000	Allen et al.
5,882,786 A	3/1999	Nassau et al.	6,110,530 A	8/2000	Chen et al.
5,883,012 A	3/1999	Chiou	6,110,832 A	8/2000	Morgan et al.
5,885,404 A	3/1999	Kim et al.	6,110,836 A	8/2000	Cohen et al.
5,885,749 A	3/1999	Huggins et al.	6,110,838 A	8/2000	Loewenstein
5,888,906 A	3/1999	Sandhu et al.	6,113,771 A	9/2000	Landau et al.
5,891,349 A	4/1999	Tobe et al.	6,117,245 A	9/2000	Mandrekar et al.
5,891,513 A	4/1999	Dubin et al.	6,120,640 A	9/2000	Shih et al.
5,897,751 A	4/1999	Makowiecki	6,136,163 A	10/2000	Cheung et al.
5,899,752 A	5/1999	Hey et al.	6,136,685 A	10/2000	Narwankar et al.
5,900,163 A	5/1999	Yi et al.	6,136,693 A	10/2000	Chan et al.
5,904,827 A	5/1999	Reynolds	6,140,234 A	10/2000	Uzoh et al.
5,907,790 A	5/1999	Kellam	6,144,099 A	11/2000	Lopatin et al.
5,910,340 A	6/1999	Uchida et al.	6,147,009 A	11/2000	Grill et al.
5,913,147 A	6/1999	Dubin et al.	6,149,828 A	11/2000	Vaartstra
5,915,190 A	6/1999	Pirkle	6,150,628 A	11/2000	Smith et al.
5,918,116 A	6/1999	Chittipeddi	6,153,935 A	11/2000	Edelstein et al.
5,920,792 A	7/1999	Lin	6,161,576 A	12/2000	Maher et al.
5,926,737 A	7/1999	Ameen et al.	6,165,912 A	12/2000	McConnell et al.
5,932,077 A	8/1999	Reynolds	6,167,834 B1	1/2001	Wang et al.
5,933,757 A	8/1999	Yoshikawa et al.	6,169,021 B1	1/2001	Akram et al.
5,935,334 A	8/1999	Fong et al.	6,170,428 B1	1/2001	Redeker et al.
5,937,323 A	8/1999	Orczyk et al.	6,171,661 B1	1/2001	Zheng et al.
5,939,831 A	8/1999	Fong et al.	6,174,450 B1	1/2001	Patrick et al.
5,942,075 A	8/1999	Nagahata et al.	6,174,812 B1	1/2001	Hsiung et al.
			6,176,198 B1	1/2001	Kao et al.
			6,176,667 B1	1/2001	Fairbairn
			6,177,245 B1	1/2001	Ward et al.
			6,179,924 B1	1/2001	Zhao et al.



(56)

## References Cited

## U.S. PATENT DOCUMENTS

6,180,523 B1	1/2001	Lee et al.	6,415,736 B1	7/2002	Hao et al.
6,182,602 B1	2/2001	Redeker et al.	6,416,647 B1	7/2002	Dordi et al.
6,184,121 B1	2/2001	Buchwalter et al.	6,418,874 B1	7/2002	Cox et al.
6,186,091 B1	2/2001	Chu et al.	6,423,284 B1	7/2002	Arno
6,189,483 B1	2/2001	Ishikawa et al.	6,427,623 B2	8/2002	Ko
6,190,233 B1	2/2001	Hong et al.	6,432,819 B1	8/2002	Pavate et al.
6,194,038 B1	2/2001	Rossmann	6,432,831 B2	8/2002	Dhindsa et al.
6,197,181 B1	3/2001	Chen	6,436,193 B1	8/2002	Kasai et al.
6,197,364 B1	3/2001	Paunovic et al.	6,436,816 B1	8/2002	Lee et al.
6,197,680 B1	3/2001	Lin et al.	6,440,863 B1	8/2002	Tsai et al.
6,197,688 B1	3/2001	Simpson	6,441,492 B1	8/2002	Cunningham
6,197,705 B1	3/2001	Vassiliev	6,446,572 B1	9/2002	Brcka
6,203,863 B1	3/2001	Liu et al.	6,448,537 B1	9/2002	Nering
6,204,200 B1	3/2001	Shieh et al.	6,458,718 B1	10/2002	Todd
6,210,486 B1	4/2001	Mizukami et al.	6,461,974 B1	10/2002	Ni et al.
6,217,658 B1	4/2001	Orczyk et al.	6,462,371 B1	10/2002	Weimer et al.
6,220,201 B1	4/2001	Nowak	6,465,051 B1	10/2002	Sahin et al.
6,228,233 B1	5/2001	Lakshmikanthan et al.	6,465,366 B1	10/2002	Nemani et al.
6,228,751 B1	5/2001	Yamazaki et al.	6,477,980 B1	11/2002	White et al.
6,228,758 B1	5/2001	Pellerin et al.	6,479,373 B2	11/2002	Dreybrodt et al.
6,235,643 B1	5/2001	Mui et al.	6,488,984 B1	12/2002	Wada et al.
6,237,527 B1	5/2001	Kellerman et al.	6,494,959 B1	12/2002	Samoilov et al.
6,238,513 B1	5/2001	Arnold et al.	6,499,425 B1	12/2002	Sandhu et al.
6,238,582 B1	5/2001	Williams et al.	6,500,728 B1	12/2002	Wang
6,241,845 B1	6/2001	Gadgil et al.	6,503,843 B1	1/2003	Xia et al.
6,242,349 B1	6/2001	Nogami et al.	6,506,291 B2	1/2003	Tsai et al.
6,244,211 B1	6/2001	Nishikawa et al.	6,509,623 B2	1/2003	Zhao
6,245,396 B1	6/2001	Nogami	6,516,815 B1	2/2003	Stevens et al.
6,245,670 B1	6/2001	Cheung et al.	6,518,548 B2	2/2003	Sugaya et al.
6,251,236 B1	6/2001	Stevens	6,527,968 B1	3/2003	Wang et al.
6,251,802 B1	6/2001	Moore et al.	6,528,409 B1	3/2003	Lopatin et al.
6,258,220 B1	7/2001	Dordi et al.	6,537,733 B2	3/2003	Campana et al.
6,258,223 B1	7/2001	Cheung et al.	6,541,397 B1	4/2003	Bencher
6,258,270 B1	7/2001	Hilgendorff et al.	6,541,671 B1	4/2003	Martinez et al.
6,261,637 B1	7/2001	Oberle	6,544,340 B2	4/2003	Yudovsky
6,277,733 B1	8/2001	Smith	6,547,977 B1	4/2003	Yan et al.
6,277,752 B1	8/2001	Chen	6,551,924 B1	4/2003	Dalton et al.
6,277,763 B1	8/2001	Kugimiya et al.	6,558,564 B1	5/2003	Loewenhardt
6,281,072 B1	8/2001	Li et al.	6,565,729 B2	5/2003	Chen et al.
6,281,135 B1	8/2001	Han et al.	6,569,773 B1	5/2003	Gellrich et al.
6,284,146 B1	9/2001	Kim et al.	6,573,030 B1	6/2003	Fairbairn et al.
6,291,282 B1	9/2001	Wilk et al.	6,573,606 B2	6/2003	Sambucetti et al.
6,291,348 B1	9/2001	Lopatin et al.	6,585,851 B1	7/2003	Ohmi et al.
6,303,044 B1	10/2001	Koentzopoulos	6,586,163 B1	7/2003	Okabe et al.
6,303,418 B1	10/2001	Cha et al.	6,596,599 B1	7/2003	Guo
6,306,772 B1	10/2001	Lin	6,596,654 B1	7/2003	Bayman et al.
6,312,554 B1	11/2001	Ye	6,602,434 B1	8/2003	Hung et al.
6,312,995 B1	11/2001	Yu	6,603,269 B1	8/2003	Vo et al.
6,319,387 B1	11/2001	Krishnamoorthy et al.	6,605,874 B2	8/2003	Leu et al.
6,321,587 B1	11/2001	Laush	6,616,967 B1	9/2003	Test
6,322,716 B1	11/2001	Qiao et al.	6,627,532 B1	9/2003	Gaillard et al.
6,323,128 B1	11/2001	Sambucetti et al.	6,635,578 B1	10/2003	Xu et al.
6,335,288 B1	1/2002	Kwan et al.	6,638,810 B2	10/2003	Bakli et al.
6,340,435 B1	1/2002	Bjorkman et al.	6,645,301 B2	11/2003	Sainty et al.
6,342,733 B1	1/2002	Hu et al.	6,645,550 B1	11/2003	Cheung et al.
RE37,546 E	2/2002	Mahawill	6,656,831 B1	12/2003	Lee et al.
6,344,410 B1	2/2002	Lopatin et al.	6,656,837 B2	12/2003	Xu et al.
6,348,407 B1	2/2002	Gupta et al.	6,663,715 B1	12/2003	Yuda et al.
6,350,320 B1	2/2002	Sherstinsky et al.	6,677,242 B1	1/2004	Liu et al.
6,350,697 B1	2/2002	Richardson	6,679,981 B1	1/2004	Pan et al.
6,351,013 B1	2/2002	Luning et al.	6,688,375 B1	2/2004	Turner
6,352,081 B1	3/2002	Lu et al.	6,713,356 B1	3/2004	Skotnicki et al.
6,355,573 B1	3/2002	Okumura	6,713,835 B1	3/2004	Horak et al.
6,364,949 B1	4/2002	Or et al.	6,717,189 B2	4/2004	Inoue et al.
6,364,954 B2	4/2002	Umotoy et al.	6,720,213 B1	4/2004	Gambino et al.
6,364,957 B1	4/2002	Schneider et al.	6,740,585 B2	5/2004	Yoon et al.
6,375,748 B1	4/2002	Yudovsky et al.	6,740,977 B2	5/2004	Ahn et al.
6,376,386 B1	4/2002	Oshima	6,743,473 B1	6/2004	Parkhe et al.
6,379,575 B1	4/2002	Yin et al.	6,743,732 B1	6/2004	Lin et al.
6,383,896 B1	5/2002	Kirimura et al.	6,756,235 B1	6/2004	Liu et al.
6,383,951 B1	5/2002	Li	6,759,261 B2	7/2004	Shimokohbe et al.
6,387,207 B1	5/2002	Janakiraman et al.	6,762,127 B2	7/2004	Boiteux et al.
6,391,753 B1	5/2002	Yu	6,762,435 B2	7/2004	Towle
6,395,150 B1	5/2002	Van Cleemput et al.	6,764,958 B1	7/2004	Nemani et al.
6,403,491 B1	6/2002	Liu et al.	6,765,273 B1	7/2004	Chau et al.
			6,767,834 B2	7/2004	Chung et al.
			6,770,166 B1	8/2004	Fisher
			6,772,827 B2	8/2004	Keller et al.
			6,792,889 B2	9/2004	Nakano et al.



(56)

## References Cited

## U.S. PATENT DOCUMENTS

6,794,290 B1	9/2004	Papasouliotis et al.	7,484,473 B2	2/2009	Keller et al.
6,794,311 B2	9/2004	Huang et al.	7,488,688 B2	2/2009	Chung et al.
6,796,314 B1	9/2004	Graff et al.	7,494,545 B2	2/2009	Lam et al.
6,797,189 B2	9/2004	Hung et al.	7,500,445 B2	3/2009	Zhao et al.
6,800,336 B1	10/2004	Fornsel et al.	7,553,756 B2	6/2009	Hayashi et al.
6,800,830 B2	10/2004	Mahawili	7,575,007 B2	8/2009	Tang et al.
6,802,944 B2	10/2004	Ahmad et al.	7,581,511 B2	9/2009	Mardian et al.
6,808,564 B2	10/2004	Dietze	7,604,708 B2	10/2009	Wood et al.
6,808,748 B2	10/2004	Kapoor et al.	7,611,980 B2	11/2009	Wells
6,821,571 B2	11/2004	Huang	7,628,897 B2	12/2009	Mungekar et al.
6,823,589 B2	11/2004	White et al.	7,682,518 B2	3/2010	Chandrachood et al.
6,830,624 B2	12/2004	Janakiraman et al.	7,695,590 B2	4/2010	Hanawa et al.
6,835,995 B2	12/2004	Li	7,708,859 B2	5/2010	Huang et al.
6,846,745 B1	1/2005	Papasouliotis et al.	7,722,925 B2	5/2010	White et al.
6,849,854 B2	2/2005	Sainty	7,723,221 B2	5/2010	Hayashi
6,852,550 B2	2/2005	Tuttle et al.	7,749,326 B2	7/2010	Kim et al.
6,858,153 B2	2/2005	Bjorkman et al.	7,785,672 B2	8/2010	Choi et al.
6,861,097 B1	3/2005	Goosey et al.	7,790,634 B2	9/2010	Munro et al.
6,861,332 B2	3/2005	Park et al.	7,806,077 B2	10/2010	Lee et al.
6,869,880 B2	3/2005	Krishnaraj et al.	7,806,078 B2	10/2010	Yoshida
6,875,280 B2	4/2005	Ikeda et al.	7,807,578 B2	10/2010	Bencher et al.
6,878,206 B2	4/2005	Tzu et al.	7,825,038 B2	11/2010	Ingle et al.
6,879,981 B2	4/2005	Rothschild et al.	7,837,828 B2	11/2010	Ikeda et al.
6,886,491 B2	5/2005	Kim et al.	7,845,309 B2	12/2010	Condrashoff et al.
6,892,669 B2	5/2005	Xu et al.	7,915,139 B1	3/2011	Lang et al.
6,893,967 B1	5/2005	Wright et al.	7,932,181 B2	4/2011	Singh et al.
6,897,532 B1	5/2005	Schwarz et al.	7,939,422 B2	5/2011	Ingle et al.
6,900,596 B2	5/2005	Yang et al.	7,968,441 B2	6/2011	Xu
6,903,511 B2	6/2005	Chistyakov	7,976,631 B2	7/2011	Burrows
6,908,862 B2	6/2005	Li et al.	7,981,806 B2	7/2011	Jung
6,911,112 B2	6/2005	An	7,989,365 B2	8/2011	Park et al.
6,911,401 B2	6/2005	Khandan et al.	8,008,166 B2	8/2011	Sanchez et al.
6,921,556 B2	7/2005	Shimizu et al.	8,048,811 B2	11/2011	Feustel et al.
6,924,191 B2	8/2005	Liu et al.	8,058,179 B1	11/2011	Draeger et al.
6,930,047 B2	8/2005	Yamazaki	8,071,482 B2	12/2011	Kawada
6,935,269 B2	8/2005	Lee et al.	8,074,599 B2	12/2011	Choi et al.
6,942,753 B2	9/2005	Choi et al.	8,076,198 B2	12/2011	Lee et al.
6,946,033 B2	9/2005	Tsuel et al.	8,083,853 B2	12/2011	Choi et al.
6,951,821 B2	10/2005	Hamelin et al.	8,114,245 B2	2/2012	Ohmi et al.
6,958,175 B2	10/2005	Sakamoto et al.	8,119,530 B2	2/2012	Hori et al.
6,958,286 B2	10/2005	Chen et al.	8,133,349 B1	3/2012	Panagopoulos
6,995,073 B2	2/2006	Liou	8,183,134 B2	5/2012	Wu
7,017,269 B2	3/2006	White et al.	8,187,486 B1	5/2012	Liu et al.
7,018,941 B2	3/2006	Cui et al.	8,211,808 B2	7/2012	Sapre et al.
7,030,034 B2	4/2006	Fucsko et al.	8,272,346 B2	9/2012	Bettencourt et al.
7,049,200 B2	5/2006	Arghavani et al.	8,298,627 B2	10/2012	Minami et al.
7,071,532 B2	7/2006	Geffken et al.	8,309,440 B2	11/2012	Sanchez et al.
7,084,070 B1	8/2006	Lee et al.	8,312,839 B2	11/2012	Baek
7,115,525 B2	10/2006	Abatchev et al.	8,313,610 B2	11/2012	Dhindsa
7,122,949 B2	10/2006	Strikovski	8,328,939 B2	12/2012	Choi et al.
7,145,725 B2	12/2006	Hasel et al.	8,357,435 B2	1/2013	Lubomirsky
7,148,155 B1	12/2006	Tarafdar et al.	8,368,308 B2	2/2013	Banna et al.
7,166,233 B2	1/2007	Johnson et al.	8,390,980 B2	3/2013	Sansoni et al.
7,183,214 B2	2/2007	Nam et al.	8,427,067 B2	4/2013	Espiau et al.
7,196,342 B2	3/2007	Ershov et al.	8,435,902 B2	5/2013	Tang et al.
7,226,805 B2	6/2007	Hallin et al.	8,475,674 B2	7/2013	Thadani et al.
7,235,137 B2	6/2007	Kitayama et al.	8,480,850 B2	7/2013	Tyler et al.
7,244,474 B2	7/2007	Hanawa et al.	8,491,805 B2	7/2013	Kushibiki et al.
7,252,011 B2	8/2007	Traverso	8,501,629 B2	8/2013	Tang et al.
7,252,716 B2	8/2007	Kim et al.	8,506,713 B2	8/2013	Takagi
7,253,123 B2	8/2007	Arghavani et al.	8,512,509 B2	8/2013	Bera et al.
7,256,370 B2	8/2007	Guiver	8,540,844 B2	9/2013	Hudson et al.
7,288,482 B2	10/2007	Panda et al.	8,551,891 B2	10/2013	Liang
7,291,360 B2	11/2007	Hanawa et al.	8,573,152 B2	11/2013	De La Llera
7,316,761 B2	1/2008	Doan et al.	8,622,021 B2	1/2014	Taylor et al.
7,329,608 B2	2/2008	Babayán et al.	8,623,148 B2	1/2014	Mitchell et al.
7,341,633 B2	3/2008	Lubomirsky et al.	8,623,471 B2	1/2014	Tyler et al.
7,344,912 B1	3/2008	Okoronyanwu	8,642,481 B2	2/2014	Wang et al.
7,358,192 B2	4/2008	Merry et al.	8,652,298 B2	2/2014	Dhindsa et al.
7,364,956 B2	4/2008	Saito	8,679,982 B2	3/2014	Wang et al.
7,365,016 B2	4/2008	Ouellet et al.	8,679,983 B2	3/2014	Wang et al.
7,396,480 B2	7/2008	Kao et al.	8,702,902 B2	4/2014	Blom et al.
7,416,989 B1	8/2008	Liu et al.	8,741,778 B2	6/2014	Yang et al.
7,465,358 B2	12/2008	Weidman et al.	8,747,680 B1	6/2014	Deshpande
7,468,319 B2	12/2008	Lee	8,765,574 B2	7/2014	Zhang et al.
			8,771,536 B2	7/2014	Zhang et al.
			8,771,539 B2	7/2014	Zhang et al.
			8,772,888 B2	7/2014	Jung et al.
			8,778,079 B2	7/2014	Begarney et al.



(56)

## References Cited

## U.S. PATENT DOCUMENTS

8,801,952 B1	8/2014	Wang et al.	9,396,989 B2	7/2016	Purayath et al.
8,808,563 B2	8/2014	Wang et al.	9,406,523 B2	8/2016	Chen et al.
8,846,163 B2	9/2014	Kao et al.	9,412,608 B2	8/2016	Wang et al.
8,869,742 B2	10/2014	Dhindsa	9,418,858 B2	8/2016	Wang et al.
8,871,651 B1	10/2014	Choi et al.	9,425,058 B2	8/2016	Kim et al.
8,895,449 B1	11/2014	Zhu et al.	9,437,451 B2	9/2016	Chen et al.
8,900,364 B2	12/2014	Wright	9,449,845 B2	9/2016	Liu et al.
8,921,234 B2	12/2014	Liu et al.	9,449,846 B2	9/2016	Liu et al.
8,927,390 B2	1/2015	Sapre et al.	9,449,850 B2	9/2016	Wang et al.
8,951,429 B1	2/2015	Liu et al.	9,472,412 B2	10/2016	Zhang et al.
8,956,980 B1	2/2015	Chen et al.	9,472,417 B2	10/2016	Ingle et al.
8,969,212 B2	3/2015	Ren et al.	2001/0008803 A1	7/2001	Takamatsu et al.
8,980,005 B2	3/2015	Carlson et al.	2001/0015261 A1	8/2001	Kobayashi et al.
8,980,758 B1	3/2015	Ling et al.	2001/0028093 A1	10/2001	Yamazaki et al.
8,980,763 B2	3/2015	Wang et al.	2001/0028922 A1	10/2001	Sandhu
8,992,723 B2	3/2015	Sorensen et al.	2001/0030366 A1	10/2001	Nakano et al.
8,999,839 B2	4/2015	Su et al.	2001/0034106 A1	10/2001	Moise et al.
8,999,856 B2	4/2015	Zhang et al.	2001/0034121 A1	10/2001	Fu et al.
9,012,302 B2	4/2015	Sapre et al.	2001/0035124 A1	11/2001	Okayama et al.
9,017,481 B1	4/2015	Pettinger et al.	2001/0036706 A1	11/2001	Kitamura
9,023,732 B2	5/2015	Wang et al.	2001/0037856 A1	11/2001	Park
9,023,734 B2	5/2015	Chen et al.	2001/0037941 A1	11/2001	Thompson
9,034,770 B2	5/2015	Park et al.	2001/0041444 A1	11/2001	Shields et al.
9,040,422 B2	5/2015	Wang et al.	2001/0047760 A1	12/2001	Moslehl
9,064,815 B2	6/2015	Zhang et al.	2001/0053585 A1	12/2001	Kikuchi et al.
9,064,816 B2	6/2015	Kim et al.	2001/0053610 A1	12/2001	Athavale
9,072,158 B2	6/2015	Ikeda et al.	2001/0054381 A1	12/2001	Umotoy et al.
9,093,371 B2	7/2015	Wang et al.	2001/0055842 A1	12/2001	Uh et al.
9,093,390 B2	7/2015	Wang et al.	2002/0000202 A1	1/2002	Yuda et al.
9,111,877 B2	8/2015	Chen et al.	2002/0011210 A1	1/2002	Satoh et al.
9,111,907 B2	8/2015	Kamineni	2002/0011214 A1	1/2002	Kamarehi et al.
9,114,438 B2	8/2015	Hoinkis et al.	2002/0016080 A1	2/2002	Khan et al.
9,117,855 B2	8/2015	Cho et al.	2002/0016085 A1	2/2002	Huang et al.
9,132,436 B2	9/2015	Liang et al.	2002/0023899 A1	2/2002	Khater et al.
9,136,273 B1	9/2015	Purayath et al.	2002/0028582 A1	3/2002	Nallan et al.
9,144,147 B2	9/2015	Yang et al.	2002/0028585 A1	3/2002	Chung et al.
9,153,442 B2	10/2015	Wang et al.	2002/0029747 A1	3/2002	Powell et al.
9,159,606 B1	10/2015	Purayath et al.	2002/0033233 A1	3/2002	Savas
9,165,786 B1	10/2015	Purayath et al.	2002/0036143 A1	3/2002	Segawa et al.
9,184,055 B2	11/2015	Wang et al.	2002/0040764 A1	4/2002	Kwan et al.
9,190,293 B2	11/2015	Wang et al.	2002/0040766 A1	4/2002	Takahashi
9,190,302 B2	11/2015	Ni	2002/0043690 A1	4/2002	Doyle et al.
9,209,012 B2	12/2015	Chen et al.	2002/0045966 A1	4/2002	Lee et al.
9,236,265 B2	1/2016	Korolik et al.	2002/0054962 A1	5/2002	Huang
9,236,266 B2	1/2016	Zhang et al.	2002/0069820 A1	6/2002	Yudovsky
9,245,762 B2	1/2016	Zhang et al.	2002/0070414 A1	6/2002	Drescher et al.
9,263,278 B2	2/2016	Purayath et al.	2002/0074573 A1	6/2002	Takeuchi et al.
9,269,590 B2	2/2016	Luere et al.	2002/0090781 A1	7/2002	Skotnicki et al.
9,275,834 B1	3/2016	Park et al.	2002/0090835 A1	7/2002	Chakravarti et al.
9,287,095 B2	3/2016	Nguyen et al.	2002/0094378 A1	7/2002	O'Donnell
9,287,134 B2	3/2016	Wang et al.	2002/0094591 A1	7/2002	Sill et al.
9,293,568 B2	3/2016	Ko	2002/0096493 A1	7/2002	Hattori
9,299,537 B2	3/2016	Kobayashi et al.	2002/0098681 A1	7/2002	Hu et al.
9,299,538 B2	3/2016	Kobayashi et al.	2002/0106845 A1	8/2002	Chao et al.
9,299,575 B2	3/2016	Park et al.	2002/0112819 A1	8/2002	Kamarehi et al.
9,299,582 B2	3/2016	Ingle et al.	2002/0124867 A1	9/2002	Kim et al.
9,299,583 B1	3/2016	Wang et al.	2002/0129769 A1	9/2002	Kim et al.
9,309,598 B2	4/2016	Wang et al.	2002/0129902 A1	9/2002	Babayan et al.
9,324,576 B2	4/2016	Zhang et al.	2002/0144657 A1	10/2002	Chiang et al.
9,343,272 B1	5/2016	Pandit et al.	2002/0153808 A1	10/2002	Skotnicki et al.
9,343,327 B2	5/2016	Zhang et al.	2002/0164885 A1	11/2002	Lill et al.
9,349,605 B1	5/2016	Xu et al.	2002/0177322 A1	11/2002	Li et al.
9,355,856 B2	5/2016	Wang et al.	2002/0187280 A1	12/2002	Johnson et al.
9,355,862 B2	5/2016	Pandit et al.	2002/0187655 A1	12/2002	Tan et al.
9,355,863 B2	5/2016	Chen et al.	2003/0003757 A1	1/2003	Naltan et al.
9,355,922 B2	5/2016	Park et al.	2003/0007910 A1	1/2003	Lazarovich et al.
9,362,130 B2	6/2016	Ingle et al.	2003/0010645 A1	1/2003	Ting et al.
9,368,364 B2	6/2016	Park et al.	2003/0019428 A1	1/2003	Ku et al.
9,373,517 B2	6/2016	Yang et al.	2003/0019580 A1	1/2003	Strang
9,373,522 B1	6/2016	Wang et al.	2003/0026060 A1	2/2003	Hiramatsu et al.
9,378,969 B2	6/2016	Hsu et al.	2003/0029566 A1	2/2003	Roth
9,378,978 B2	6/2016	Purayath et al.	2003/0029567 A1	2/2003	Dhindsa et al.
9,384,997 B2	7/2016	Ren et al.	2003/0029715 A1	2/2003	Yu et al.
9,385,028 B2	7/2016	Nemani et al.	2003/0032284 A1	2/2003	Enomoto et al.
9,390,937 B2	7/2016	Chen et al.	2003/0038127 A1	2/2003	Liu et al.
			2003/0038305 A1	2/2003	Wasshuber
			2003/0054608 A1	3/2003	Tseng et al.
			2003/0071035 A1	4/2003	Brailove
			2003/0072639 A1	4/2003	White et al.



(56)

## References Cited

## U.S. PATENT DOCUMENTS

2003/0075808	A1	4/2003	Inoue et al.	2004/0263827	A1	12/2004	Xu
2003/0077909	A1	4/2003	Jiwari	2005/0001276	A1	1/2005	Gao et al.
2003/0079686	A1	5/2003	Chen et al.	2005/0003676	A1	1/2005	Ho et al.
2003/0087531	A1	5/2003	Kang et al.	2005/0009340	A1	1/2005	Saijo et al.
2003/0091938	A1	5/2003	Fairbairn et al.	2005/0009358	A1	1/2005	Choi et al.
2003/0098125	A1	5/2003	An	2005/0026430	A1	2/2005	Kim et al.
2003/0109143	A1	6/2003	Hsieh et al.	2005/0026431	A1	2/2005	Kazumi et al.
2003/0116087	A1	6/2003	Nguyen et al.	2005/0035455	A1	2/2005	Hu et al.
2003/0116439	A1	6/2003	Seo et al.	2005/0051094	A1	3/2005	Schaepkens et al.
2003/0121608	A1	7/2003	Chen et al.	2005/0073051	A1	4/2005	Yamamoto et al.
2003/0121609	A1	7/2003	Ohmi et al.	2005/0079706	A1	4/2005	Kumar et al.
2003/0124465	A1	7/2003	Lee et al.	2005/0090078	A1	4/2005	Ishihara
2003/0124842	A1	7/2003	Hytros et al.	2005/0090120	A1	4/2005	Hasegawa et al.
2003/0127740	A1	7/2003	Hsu et al.	2005/0098111	A1	5/2005	Shimizu et al.
2003/0129106	A1	7/2003	Sorensen et al.	2005/0105991	A1	5/2005	Hofmeister et al.
2003/0129827	A1	7/2003	Lee et al.	2005/0112876	A1	5/2005	Wu
2003/0132319	A1	7/2003	Hytros et al.	2005/0112901	A1	5/2005	Ji et al.
2003/0140844	A1	7/2003	Maa et al.	2005/0164479	A1	7/2005	Perng et al.
2003/0143328	A1	7/2003	Chen et al.	2005/0167394	A1	8/2005	Liu et al.
2003/0148035	A1	8/2003	Lingampalli	2005/0181588	A1	8/2005	Kim
2003/0152691	A1	8/2003	Baude	2005/0196967	A1	9/2005	Savas et al.
2003/0159307	A1	8/2003	Sago et al.	2005/0199489	A1	9/2005	Stevens et al.
2003/0168439	A1	9/2003	Kanno et al.	2005/0205110	A1	9/2005	Kao et al.
2003/0170945	A1	9/2003	Igeta et al.	2005/0205862	A1	9/2005	Koemtzopoulos et al.
2003/0173333	A1	9/2003	Wang et al.	2005/0208215	A1	9/2005	Eguchi et al.
2003/0173347	A1	9/2003	Guiver	2005/0214477	A1	9/2005	Hanawa et al.
2003/0173675	A1	9/2003	Watanabe	2005/0218507	A1	10/2005	Kao et al.
2003/0181040	A1	9/2003	Ivanov et al.	2005/0219786	A1	10/2005	Brown et al.
2003/0183244	A1	10/2003	Rossmann	2005/0221552	A1	10/2005	Kao et al.
2003/0190426	A1	10/2003	Padhi et al.	2005/0230350	A1	10/2005	Kao et al.
2003/0199170	A1	10/2003	Li	2005/0236694	A1	10/2005	Wu et al.
2003/0200929	A1	10/2003	Otsuki	2005/0239282	A1	10/2005	Chen et al.
2003/0205329	A1	11/2003	Gujer et al.	2005/0251990	A1	11/2005	Choi et al.
2003/0215963	A1	11/2003	AmRhein et al.	2005/0266622	A1	12/2005	Arghavani et al.
2003/0216044	A1	11/2003	Lin et al.	2005/0266691	A1	12/2005	Gu et al.
2003/0221780	A1	12/2003	Lei et al.	2005/0269030	A1	12/2005	Kent et al.
2003/0224217	A1	12/2003	Byun et al.	2005/0274324	A1	12/2005	Takahashi et al.
2003/0224617	A1	12/2003	Baek et al.	2005/0279454	A1	12/2005	Snijders
2004/0005726	A1	1/2004	Huang	2005/0287755	A1	12/2005	Bachmann
2004/0018304	A1	1/2004	Chung et al.	2005/0287771	A1	12/2005	Seamons et al.
2004/0020801	A1	2/2004	Zhao et al.	2006/0000802	A1	1/2006	Kumar et al.
2004/0026371	A1	2/2004	Nguyen et al.	2006/0000805	A1	1/2006	Todorow et al.
2004/0033678	A1	2/2004	Arghavani et al.	2006/0005856	A1	1/2006	Sun et al.
2004/0033684	A1	2/2004	Li	2006/0005930	A1	1/2006	Ikeda et al.
2004/0050328	A1	3/2004	Kumagai et al.	2006/0006057	A1	1/2006	Laermer
2004/0058293	A1	3/2004	Nguyen et al.	2006/0011298	A1	1/2006	Lim et al.
2004/0069225	A1	4/2004	Fairbairn et al.	2006/0011299	A1	1/2006	Condrashoff et al.
2004/0070346	A1	4/2004	Choi	2006/0016783	A1	1/2006	Wu et al.
2004/0072446	A1	4/2004	Liu et al.	2006/0019456	A1	1/2006	Bu et al.
2004/0076529	A1	4/2004	Gnauck et al.	2006/0019486	A1	1/2006	Yu et al.
2004/0083967	A1	5/2004	Yuda et al.	2006/0021574	A1	2/2006	Armour et al.
2004/0087139	A1	5/2004	Yeh et al.	2006/0024954	A1	2/2006	Wu et al.
2004/0092063	A1	5/2004	Okumura	2006/0024956	A1	2/2006	Zhijian et al.
2004/0099378	A1	5/2004	Kim et al.	2006/0033678	A1	2/2006	Lubomirsky et al.
2004/0101667	A1	5/2004	O'Loughlin et al.	2006/0040055	A1	2/2006	Nguyen et al.
2004/0108068	A1	6/2004	Senzaki et al.	2006/0043066	A1	3/2006	Kamp
2004/0115876	A1	6/2004	Goundar et al.	2006/0046412	A1	3/2006	Nguyen et al.
2004/0129671	A1	7/2004	Ji et al.	2006/0046419	A1	3/2006	Sandhu et al.
2004/0137161	A1	7/2004	Segawa et al.	2006/0046470	A1	3/2006	Becknell
2004/0144490	A1	7/2004	Zhao et al.	2006/0051966	A1	3/2006	Or et al.
2004/0147126	A1	7/2004	Yamashita et al.	2006/0051968	A1	3/2006	Joshi et al.
2004/0149394	A1	8/2004	Doan et al.	2006/0054184	A1	3/2006	Mozetic et al.
2004/0152342	A1	8/2004	Li	2006/0060942	A1	3/2006	Minixhofer et al.
2004/0154535	A1	8/2004	Chen et al.	2006/0087644	A1	4/2006	McMillin et al.
2004/0157444	A1	8/2004	Chiu	2006/0093756	A1	5/2006	Rajagopalan et al.
2004/0161921	A1	8/2004	Ryu	2006/0097397	A1	5/2006	Russell et al.
2004/0175913	A1	9/2004	Johnson et al.	2006/0102076	A1	5/2006	Smith et al.
2004/0175929	A1	9/2004	Schmitt et al.	2006/0102587	A1	5/2006	Kimura
2004/0182315	A1	9/2004	Laflamme et al.	2006/0118178	A1	6/2006	Desbiolles et al.
2004/0192032	A1	9/2004	Ohmori et al.	2006/0121724	A1	6/2006	Yue et al.
2004/0194799	A1	10/2004	Kim et al.	2006/0124242	A1	6/2006	Kanarik et al.
2004/0200499	A1	10/2004	Harvey	2006/0130971	A1	6/2006	Chang et al.
2004/0211357	A1	10/2004	Gadgil et al.	2006/0157449	A1	7/2006	Takahashi et al.
2004/0219737	A1	11/2004	Quon	2006/0162661	A1	7/2006	Jung et al.
2004/0219789	A1	11/2004	Wood et al.	2006/0166107	A1	7/2006	Chen et al.
				2006/0166515	A1	7/2006	Karim et al.
				2006/0169327	A1	8/2006	Shajii et al.
				2006/0178008	A1	8/2006	Yeh et al.
				2006/0185592	A1	8/2006	Matsuura



(56)

## References Cited

## U.S. PATENT DOCUMENTS

2006/0191479	A1	8/2006	Mizukami et al.	2008/0115726	A1	5/2008	Ingle et al.
2006/0191637	A1	8/2006	Zajac et al.	2008/0121970	A1	5/2008	Aritome
2006/0207504	A1	9/2006	Hasebe et al.	2008/0124937	A1	5/2008	Xu et al.
2006/0207595	A1	9/2006	Ohmi et al.	2008/0142483	A1	6/2008	Hua et al.
2006/0210723	A1	9/2006	Ishizaka	2008/0153306	A1	6/2008	Cho et al.
2006/0216878	A1	9/2006	Lee	2008/0156771	A1	7/2008	Jeon et al.
2006/0222481	A1	10/2006	Foree	2008/0157225	A1	7/2008	Datta et al.
2006/0226121	A1	10/2006	Aoi	2008/0160210	A1	7/2008	Yang et al.
2006/0228889	A1	10/2006	Edelberg et al.	2008/0171407	A1	7/2008	Nakabayashi et al.
2006/0240661	A1	10/2006	Annapragada et al.	2008/0173906	A1	7/2008	Zhu
2006/0244107	A1	11/2006	Sugihara	2008/0182381	A1	7/2008	Kiyotoshi
2006/0246217	A1	11/2006	Weidman et al.	2008/0182383	A1	7/2008	Lee et al.
2006/0251800	A1	11/2006	Weidman et al.	2008/0202892	A1	8/2008	Smith et al.
2006/0251801	A1	11/2006	Weidman et al.	2008/0230519	A1	9/2008	Takahashi
2006/0252252	A1	11/2006	Zhu et al.	2008/0233709	A1	9/2008	Conti et al.
2006/0252265	A1	11/2006	Jin et al.	2008/0236751	A1	10/2008	Aramaki et al.
2006/0254716	A1	11/2006	Mosden et al.	2008/0254635	A1	10/2008	Benzel et al.
2006/0260750	A1	11/2006	Rueger	2008/0261404	A1	10/2008	Kozuka et al.
2006/0261490	A1	11/2006	Su et al.	2008/0268645	A1	10/2008	Kao et al.
2006/0264043	A1	11/2006	Stewart et al.	2008/0292798	A1	11/2008	Huh et al.
2006/0266288	A1	11/2006	Choi	2008/0293248	A1	11/2008	Park et al.
2006/0292846	A1	12/2006	Pinto et al.	2009/0001480	A1	1/2009	Cheng
2007/0025907	A1	2/2007	Rezeq	2009/0004849	A1	1/2009	Eun
2007/0048977	A1	3/2007	Lee et al.	2009/0014127	A1	1/2009	Shah et al.
2007/0056925	A1	3/2007	Liu et al.	2009/0017227	A1	1/2009	Fu et al.
2007/0062453	A1	3/2007	Ishikawa	2009/0045167	A1	2/2009	Maruyama
2007/0071888	A1	3/2007	Shanmugasundram et al.	2009/0072401	A1	3/2009	Arnold et al.
2007/0072408	A1	3/2007	Enomoto et al.	2009/0081878	A1	3/2009	Dhindsa
2007/0090325	A1	4/2007	Hwang et al.	2009/0084317	A1	4/2009	Wu et al.
2007/0099428	A1	5/2007	Shamiryan et al.	2009/0087960	A1	4/2009	Cho et al.
2007/0099431	A1	5/2007	Li	2009/0087979	A1	4/2009	Raghuram
2007/0099438	A1	5/2007	Ye et al.	2009/0095621	A1	4/2009	Kao et al.
2007/0107750	A1	5/2007	Sawin et al.	2009/0098706	A1	4/2009	Kim et al.
2007/0108404	A1	5/2007	Stewart et al.	2009/0104738	A1	4/2009	Ring et al.
2007/0111519	A1	5/2007	Lubomirsky et al.	2009/0104782	A1	4/2009	Lu et al.
2007/0117396	A1	5/2007	Wu et al.	2009/0111280	A1	4/2009	Kao et al.
2007/0119370	A1	5/2007	Ma et al.	2009/0120464	A1	5/2009	Rasheed et al.
2007/0119371	A1	5/2007	Ma et al.	2009/0170221	A1	7/2009	Jacques et al.
2007/0123051	A1	5/2007	Arghavani et al.	2009/0170331	A1	7/2009	Cheng et al.
2007/0131274	A1	6/2007	Stollwerck et al.	2009/0179300	A1	7/2009	Arai
2007/0145023	A1	6/2007	Holber et al.	2009/0189246	A1	7/2009	Wu et al.
2007/0154838	A1	7/2007	Lee	2009/0194810	A1	8/2009	Kiyotoshi et al.
2007/0163440	A1	7/2007	Kim et al.	2009/0197418	A1	8/2009	Sago et al.
2007/0175861	A1	8/2007	Hwang et al.	2009/0202721	A1	8/2009	Nogami et al.
2007/0181057	A1	8/2007	Lam et al.	2009/0255902	A1	10/2009	Satoh et al.
2007/0193515	A1	8/2007	Jeon et al.	2009/0258162	A1	10/2009	Furuta et al.
2007/0197028	A1	8/2007	Byun et al.	2009/0269934	A1	10/2009	Kao et al.
2007/0207275	A1	9/2007	Nowak et al.	2009/0274590	A1	11/2009	Willwerth et al.
2007/0212288	A1	9/2007	Holst	2009/0275146	A1	11/2009	Takano et al.
2007/0227554	A1	10/2007	Satoh et al.	2009/0275205	A1	11/2009	Kiehlbauch et al.
2007/0231109	A1	10/2007	Pak et al.	2009/0275206	A1	11/2009	Katz et al.
2007/0235134	A1	10/2007	Iimuro	2009/0277587	A1	11/2009	Lubomirsky et al.
2007/0238321	A1	10/2007	Futase et al.	2009/0277874	A1	11/2009	Rui et al.
2007/0243685	A1	10/2007	Jiang et al.	2009/0280650	A1	11/2009	Lubomirsky et al.
2007/0243714	A1	10/2007	Shin et al.	2009/0286400	A1	11/2009	Heo et al.
2007/0259467	A1	11/2007	Tweet et al.	2009/0294898	A1	12/2009	Feustel et al.
2007/0264820	A1	11/2007	Liu	2009/0317978	A1	12/2009	Higashi
2007/0266946	A1	11/2007	Choi	2009/0320756	A1	12/2009	Tanaka
2007/0277734	A1	12/2007	Lubomirsky et al.	2010/0003824	A1	1/2010	Kadkhodayan et al.
2007/0281106	A1	12/2007	Lubomirsky et al.	2010/0022030	A1	1/2010	Ditizio
2007/0287292	A1	12/2007	Li et al.	2010/0047080	A1	2/2010	Bruce
2007/0296967	A1	12/2007	Gupta et al.	2010/0048027	A1	2/2010	Cheng et al.
2008/0017104	A1	1/2008	Matyushkin et al.	2010/0055408	A1	3/2010	Lee et al.
2008/0020570	A1	1/2008	Naik	2010/0055917	A1	3/2010	Kim
2008/0044990	A1	2/2008	Lee	2010/0059889	A1	3/2010	Gosset et al.
2008/0063810	A1	3/2008	Park et al.	2010/0062603	A1	3/2010	Ganguly et al.
2008/0075668	A1	3/2008	Goldstein	2010/0075503	A1	3/2010	Bencher
2008/0081483	A1	4/2008	Wu	2010/0093151	A1	4/2010	Arghavani et al.
2008/0085604	A1	4/2008	Hoshino et al.	2010/0093168	A1	4/2010	Naik
2008/0099147	A1	5/2008	Myo et al.	2010/0096367	A1	4/2010	Jeon et al.
2008/0099431	A1	5/2008	Kumar et al.	2010/0099236	A1	4/2010	Kwon et al.
2008/0099876	A1	5/2008	Seto	2010/0099263	A1	4/2010	Kao et al.
2008/0102570	A1	5/2008	Fisher et al.	2010/0101727	A1	4/2010	Ji
2008/0102640	A1	5/2008	Hassan et al.	2010/0105209	A1	4/2010	Winniczek et al.
2008/0104782	A1	5/2008	Hughes	2010/0130001	A1	5/2010	Noguchi
				2010/0144140	A1	6/2010	Chandrashekar et al.
				2010/0147219	A1	6/2010	Hsieh et al.
				2010/0164422	A1	7/2010	Shu et al.
				2010/0173499	A1	7/2010	Tao et al.



(56)

## References Cited

## U.S. PATENT DOCUMENTS

2010/0178748	A1	7/2010	Subramanian	2012/0223418	A1	9/2012	Stowers et al.
2010/0178755	A1	7/2010	Lee et al.	2012/0225557	A1	9/2012	Serry et al.
2010/0180819	A1	7/2010	Hatanaka et al.	2012/0228642	A1	9/2012	Aube et al.
2010/0183825	A1	7/2010	Becker et al.	2012/0238102	A1	9/2012	Zhang et al.
2010/0187534	A1	7/2010	Nishi et al.	2012/0238103	A1	9/2012	Zhang et al.
2010/0187588	A1	7/2010	Kim et al.	2012/0241411	A1	9/2012	Darling et al.
2010/0187694	A1	7/2010	Yu et al.	2012/0247390	A1	10/2012	Sawada et al.
2010/0190352	A1	7/2010	Jaiswal	2012/0247670	A1	10/2012	Dobashi et al.
2010/0197143	A1	8/2010	Nishimura	2012/0247671	A1	10/2012	Sugawara
2010/0203739	A1	8/2010	Becker et al.	2012/0258600	A1	10/2012	Godet et al.
2010/0207205	A1	8/2010	Grebs et al.	2012/0267346	A1	10/2012	Kao et al.
2010/0240205	A1	9/2010	Son	2012/0282779	A1	11/2012	Arnold et al.
2010/0258913	A1	10/2010	Lue	2012/0285619	A1	11/2012	Matyushkin et al.
2010/0294199	A1	11/2010	Tran et al.	2012/0285621	A1	11/2012	Tan
2010/0330814	A1	12/2010	Yokota et al.	2012/0292664	A1	11/2012	Kanike
2011/0005607	A1	1/2011	Desbiolles et al.	2012/0309204	A1	12/2012	Kang et al.
2011/0008950	A1	1/2011	Xu	2013/0001899	A1	1/2013	Hwang et al.
2011/0011338	A1	1/2011	Chuc et al.	2013/0005103	A1	1/2013	Liu et al.
2011/0034035	A1	2/2011	Liang et al.	2013/0005140	A1	1/2013	Jeng et al.
2011/0039407	A1	2/2011	Nishizuka	2013/0012032	A1	1/2013	Liu et al.
2011/0045676	A1	2/2011	Park	2013/0032574	A1	2/2013	Liu et al.
2011/0053380	A1	3/2011	Sapre et al.	2013/0034666	A1	2/2013	Liang et al.
2011/0058303	A1	3/2011	Migita	2013/0034968	A1	2/2013	Zhang et al.
2011/0061810	A1	3/2011	Ganguly et al.	2013/0045605	A1	2/2013	Wang et al.
2011/0061812	A1	3/2011	Ganguly et al.	2013/0052827	A1	2/2013	Wang et al.
2011/0065276	A1	3/2011	Ganguly et al.	2013/0052833	A1	2/2013	Ranjan et al.
2011/0081782	A1	4/2011	Liang et al.	2013/0059440	A1	3/2013	Wang et al.
2011/0100489	A1	5/2011	Orito	2013/0062675	A1	3/2013	Thomas
2011/0111596	A1	5/2011	Kanakasabapathy	2013/0065398	A1	3/2013	Ohsawa et al.
2011/0114601	A1	5/2011	Lubomirsky et al.	2013/0082197	A1	4/2013	Yang et al.
2011/0115378	A1	5/2011	Lubomirsky et al.	2013/0084654	A1	4/2013	Gaylord et al.
2011/0124144	A1	5/2011	Schlemm et al.	2013/0089988	A1	4/2013	Wang et al.
2011/0127156	A1	6/2011	Foad et al.	2013/0098868	A1	4/2013	Nishimura et al.
2011/0143542	A1	6/2011	Feurprier et al.	2013/0105948	A1	5/2013	Kewley
2011/0151674	A1	6/2011	Tang et al.	2013/0119016	A1	5/2013	Kagoshima
2011/0151677	A1	6/2011	Wang et al.	2013/0119457	A1	5/2013	Lue et al.
2011/0151678	A1	6/2011	Ashtiani et al.	2013/0119483	A1	5/2013	Alptekin et al.
2011/0155181	A1	6/2011	Inatomi	2013/0130507	A1	5/2013	Wang et al.
2011/0159690	A1	6/2011	Chandrashekar et al.	2013/0150303	A1	6/2013	Kungl et al.
2011/0165057	A1	7/2011	Honda et al.	2013/0161726	A1	6/2013	Kim et al.
2011/0165771	A1	7/2011	Ring et al.	2013/0175654	A1	7/2013	Muckenhirn et al.
2011/0180847	A1	7/2011	Ikeda et al.	2013/0187220	A1	7/2013	Surthi
2011/0195575	A1	8/2011	Wang	2013/0193108	A1	8/2013	Zheng
2011/0217851	A1	9/2011	Liang et al.	2013/0217243	A1	8/2013	Underwood et al.
2011/0226734	A1	9/2011	Sumiya et al.	2013/0224960	A1	8/2013	Payyapilly et al.
2011/0227028	A1	9/2011	Sekar et al.	2013/0260533	A1	10/2013	Sapre et al.
2011/0230052	A1	9/2011	Tang et al.	2013/0260564	A1	10/2013	Sapre et al.
2011/0232737	A1	9/2011	Ruletzki et al.	2013/0279066	A1	10/2013	Lubomirsky et al.
2011/0266252	A1	11/2011	Thadani et al.	2013/0284369	A1	10/2013	Kobayashi et al.
2011/0266682	A1	11/2011	Edelstein et al.	2013/0284370	A1	10/2013	Kobayashi et al.
2011/0294300	A1	12/2011	Zhang et al.	2013/0284373	A1	10/2013	Sun et al.
2011/0298061	A1	12/2011	Siddiqui et al.	2013/0284374	A1	10/2013	Lubomirsky et al.
2012/0003782	A1	1/2012	Byun et al.	2013/0286530	A1	10/2013	Lin et al.
2012/0009796	A1	1/2012	Cui et al.	2013/0295297	A1	11/2013	Chou et al.
2012/0025289	A1	2/2012	Liang et al.	2013/0298942	A1	11/2013	Ren et al.
2012/0031559	A1	2/2012	Dhindsa et al.	2013/0302980	A1	11/2013	Chandrashekar et al.
2012/0034786	A1	2/2012	Dhindsa et al.	2013/0337655	A1	12/2013	Lee et al.
2012/0052683	A1	3/2012	Kim et al.	2013/0343829	A1	12/2013	Benedetti et al.
2012/0068242	A1	3/2012	Shin et al.	2014/0004707	A1	1/2014	Thejoworo et al.
2012/0103518	A1	5/2012	Kakimoto	2014/0004708	A1	1/2014	Thejoworo
2012/0104564	A1	5/2012	Won et al.	2014/0020708	A1	1/2014	Kim et al.
2012/0129354	A1	5/2012	Luong	2014/0021673	A1	1/2014	Chen et al.
2012/0135576	A1	5/2012	Lee et al.	2014/0057447	A1	2/2014	Yang et al.
2012/0148369	A1	6/2012	Michalski et al.	2014/0065842	A1	3/2014	Anthis et al.
2012/0149200	A1	6/2012	Culp et al.	2014/0080308	A1	3/2014	Chen et al.
2012/0161405	A1	6/2012	Mohn et al.	2014/0080309	A1	3/2014	Park
2012/0164839	A1	6/2012	Nishimura	2014/0080310	A1	3/2014	Chen et al.
2012/0180954	A1	7/2012	Yang et al.	2014/0083362	A1	3/2014	Lubomirsky et al.
2012/0181599	A1	7/2012	Lung	2014/0087488	A1	3/2014	Nam et al.
2012/0182808	A1	7/2012	Lue et al.	2014/0097270	A1	4/2014	Liang et al.
2012/0196447	A1	8/2012	Yang et al.	2014/0099794	A1	4/2014	Ingle et al.
2012/0202408	A1	8/2012	Shajii et al.	2014/0124364	A1	5/2014	Yoo et al.
2012/0208361	A1	8/2012	Ha	2014/0134847	A1	5/2014	Seya
2012/0211462	A1	8/2012	Zhang et al.	2014/0141621	A1	5/2014	Ren et al.
2012/0223048	A1	9/2012	Paranjpe et al.	2014/0152312	A1	6/2014	Snow et al.
				2014/0166617	A1	6/2014	Chen
				2014/0166618	A1	6/2014	Tadigadapa et al.
				2014/0186772	A1	7/2014	Pohlers et al.
				2014/0190410	A1	7/2014	Kim



(56)

## References Cited

## U.S. PATENT DOCUMENTS

- |              |    |         |                        |
|--------------|----|---------|------------------------|
| 2014/0199851 | A1 | 7/2014  | Nemani et al.          |
| 2014/0225504 | A1 | 8/2014  | Kaneko et al.          |
| 2014/0227881 | A1 | 8/2014  | Lubomirsky et al.      |
| 2014/0234466 | A1 | 8/2014  | Gao et al.             |
| 2014/0248773 | A1 | 9/2014  | Tsai et al.            |
| 2014/0248780 | A1 | 9/2014  | Ingle et al.           |
| 2014/0256131 | A1 | 9/2014  | Wang et al.            |
| 2014/0256145 | A1 | 9/2014  | Abdallah et al.        |
| 2014/0262031 | A1 | 9/2014  | Belostotskiy et al.    |
| 2014/0262038 | A1 | 9/2014  | Wang et al.            |
| 2014/0263272 | A1 | 9/2014  | Duan et al.            |
| 2014/0264533 | A1 | 9/2014  | Simsek-Ege             |
| 2014/0271097 | A1 | 9/2014  | Wang et al.            |
| 2014/0273373 | A1 | 9/2014  | Makala et al.          |
| 2014/0273406 | A1 | 9/2014  | Wang et al.            |
| 2014/0273451 | A1 | 9/2014  | Wang et al.            |
| 2014/0273462 | A1 | 9/2014  | Simsek-Ege et al.      |
| 2014/0273489 | A1 | 9/2014  | Wang et al.            |
| 2014/0273491 | A1 | 9/2014  | Zhang et al.           |
| 2014/0273492 | A1 | 9/2014  | Anthis et al.          |
| 2014/0273496 | A1 | 9/2014  | Kao                    |
| 2014/0288528 | A1 | 9/2014  | Py et al.              |
| 2014/0302678 | A1 | 10/2014 | Paterson et al.        |
| 2014/0302680 | A1 | 10/2014 | Singh                  |
| 2014/0308758 | A1 | 10/2014 | Nemani et al.          |
| 2014/0308816 | A1 | 10/2014 | Wang et al.            |
| 2014/0311581 | A1 | 10/2014 | Belostotskiy et al.    |
| 2014/0342532 | A1 | 11/2014 | Zhu                    |
| 2014/0342569 | A1 | 11/2014 | Zhu et al.             |
| 2014/0349477 | A1 | 11/2014 | Chandrashekar et al.   |
| 2015/0011096 | A1 | 1/2015  | Chandrasekharan et al. |
| 2015/0014152 | A1 | 1/2015  | Hoinkis et al.         |
| 2015/0031211 | A1 | 1/2015  | Sapre et al.           |
| 2015/0037980 | A1 | 2/2015  | Rha                    |
| 2015/0060265 | A1 | 3/2015  | Cho et al.             |
| 2015/0076110 | A1 | 3/2015  | Wu et al.              |
| 2015/0076586 | A1 | 3/2015  | Rabkin et al.          |
| 2015/0079797 | A1 | 3/2015  | Chen et al.            |
| 2015/0118858 | A1 | 4/2015  | Takaba                 |
| 2015/0126035 | A1 | 5/2015  | Diao et al.            |
| 2015/0126039 | A1 | 5/2015  | Korolik et al.         |
| 2015/0126040 | A1 | 5/2015  | Korolik et al.         |
| 2015/0129541 | A1 | 5/2015  | Wang et al.            |
| 2015/0129545 | A1 | 5/2015  | Ingle et al.           |
| 2015/0129546 | A1 | 5/2015  | Ingle et al.           |
| 2015/0132953 | A1 | 5/2015  | Nowling                |
| 2015/0132968 | A1 | 5/2015  | Ren et al.             |
| 2015/0152072 | A1 | 6/2015  | Cantat et al.          |
| 2015/0155177 | A1 | 6/2015  | Zhang et al.           |
| 2015/0170879 | A1 | 6/2015  | Nguyen et al.          |
| 2015/0170920 | A1 | 6/2015  | Purayath et al.        |
| 2015/0170924 | A1 | 6/2015  | Nguyen et al.          |
| 2015/0170926 | A1 | 6/2015  | Michalak               |
| 2015/0170935 | A1 | 6/2015  | Wang et al.            |
| 2015/0170943 | A1 | 6/2015  | Nguyen et al.          |
| 2015/0171008 | A1 | 6/2015  | Luo                    |
| 2015/0179464 | A1 | 6/2015  | Wang et al.            |
| 2015/0206764 | A1 | 7/2015  | Wang et al.            |
| 2015/0214066 | A1 | 7/2015  | Luere et al.           |
| 2015/0214067 | A1 | 7/2015  | Zhang et al.           |
| 2015/0214092 | A1 | 7/2015  | Purayath et al.        |
| 2015/0214337 | A1 | 7/2015  | Ko et al.              |
| 2015/0221541 | A1 | 8/2015  | Nemani et al.          |
| 2015/0235809 | A1 | 8/2015  | Ito et al.             |
| 2015/0235863 | A1 | 8/2015  | Chen                   |
| 2015/0235865 | A1 | 8/2015  | Wang et al.            |
| 2015/0235867 | A1 | 8/2015  | Nishizuka              |
| 2015/0247231 | A1 | 9/2015  | Nguyen et al.          |
| 2015/0249018 | A1 | 9/2015  | Park et al.            |
| 2015/0270140 | A1 | 9/2015  | Gupta et al.           |
| 2015/0275361 | A1 | 10/2015 | Lubomirsky et al.      |
| 2015/0275375 | A1 | 10/2015 | Kim et al.             |
| 2015/0294980 | A1 | 10/2015 | Lee et al.             |
| 2015/0332930 | A1 | 11/2015 | Wang et al.            |
| 2015/0340225 | A1 | 11/2015 | Kim et al.             |
| 2015/0357201 | A1 | 12/2015 | Chen et al.            |
| 2015/0357205 | A1 | 12/2015 | Wang et al.            |
| 2015/0371861 | A1 | 12/2015 | Li et al.              |
| 2015/0371864 | A1 | 12/2015 | Hsu et al.             |
| 2015/0371865 | A1 | 12/2015 | Chen et al.            |
| 2015/0371866 | A1 | 12/2015 | Chen et al.            |
| 2016/0005572 | A1 | 1/2016  | Liang et al.           |
| 2016/0005833 | A1 | 1/2016  | Collins et al.         |
| 2016/0027654 | A1 | 1/2016  | Kim et al.             |
| 2016/0027673 | A1 | 1/2016  | Wang et al.            |
| 2016/0035586 | A1 | 2/2016  | Purayath et al.        |
| 2016/0035614 | A1 | 2/2016  | Purayath et al.        |
| 2016/0042968 | A1 | 2/2016  | Purayath et al.        |
| 2016/0056167 | A1 | 2/2016  | Wang et al.            |
| 2016/0064233 | A1 | 3/2016  | Wang et al.            |
| 2016/0079072 | A1 | 3/2016  | Wang et al.            |
| 2016/0086807 | A1 | 3/2016  | Park et al.            |
| 2016/0086808 | A1 | 3/2016  | Zhang et al.           |
| 2016/0086815 | A1 | 3/2016  | Pandit et al.          |
| 2016/0086816 | A1 | 3/2016  | Wang et al.            |
| 2016/0093506 | A1 | 3/2016  | Chen et al.            |
| 2016/0104606 | A1 | 4/2016  | Park et al.            |
| 2016/0118268 | A1 | 4/2016  | Ingle et al.           |
| 2016/0148821 | A1 | 5/2016  | Singh et al.           |
| 2016/0181112 | A1 | 6/2016  | Xue et al.             |
| 2016/0189933 | A1 | 6/2016  | Kobayashi et al.       |
| 2016/0204009 | A1 | 7/2016  | Nguyen et al.          |
| 2016/0218018 | A1 | 7/2016  | Lieu et al.            |
| 2016/0222522 | A1 | 8/2016  | Wang et al.            |
| 2016/0225651 | A1 | 8/2016  | Tran et al.            |
| 2016/0225652 | A1 | 8/2016  | Tran et al.            |
| 2016/0237570 | A1 | 8/2016  | Tan et al.             |
| 2016/0240389 | A1 | 8/2016  | Zhang et al.           |
| 2016/0240402 | A1 | 8/2016  | Park et al.            |
| 2016/0260588 | A1 | 9/2016  | Park et al.            |
| 2016/0260616 | A1 | 9/2016  | Li et al.              |
| 2016/0260619 | A1 | 9/2016  | Zhang et al.           |
| 2016/0284556 | A1 | 9/2016  | Ingle et al.           |

## FOREIGN PATENT DOCUMENTS

- |    |                 |    |         |
|----|-----------------|----|---------|
| JP | H01-200627      | A  | 8/1989  |
| JP | H02-114525      | A  | 4/1990  |
| JP | H07-153739      | A  | 6/1995  |
| JP | H08-264510      | A  | 10/1996 |
| JP | 2003-174020     | A  | 6/2003  |
| JP | 4763293         | B2 | 8/2011  |
| JP | 2013-243418     | A  | 12/2013 |
| KR | 10-2000-008278  | A  | 2/2000  |
| KR | 10-2005-0042701 | A  | 5/2005  |
| KR | 10-2008-0063988 | A  | 7/2008  |
| KR | 10-2009-0128913 | A  | 12/2009 |
| KR | 10-2011-0086540 | A  | 7/2011  |
| KR | 10-2011-0126675 | A  | 11/2011 |
| KR | 10-2012-0082640 | A  | 7/2012  |
| WO | 2009-084194     | A1 | 7/2009  |
| WO | 2010-010706     |    | 1/2010  |

## OTHER PUBLICATIONS

H. Xiao, Introduction to Semiconductor Manufacturing Technology, published by Prentice Hall, 2001, ISBN 0-13-022404-9, pp. 354-356.



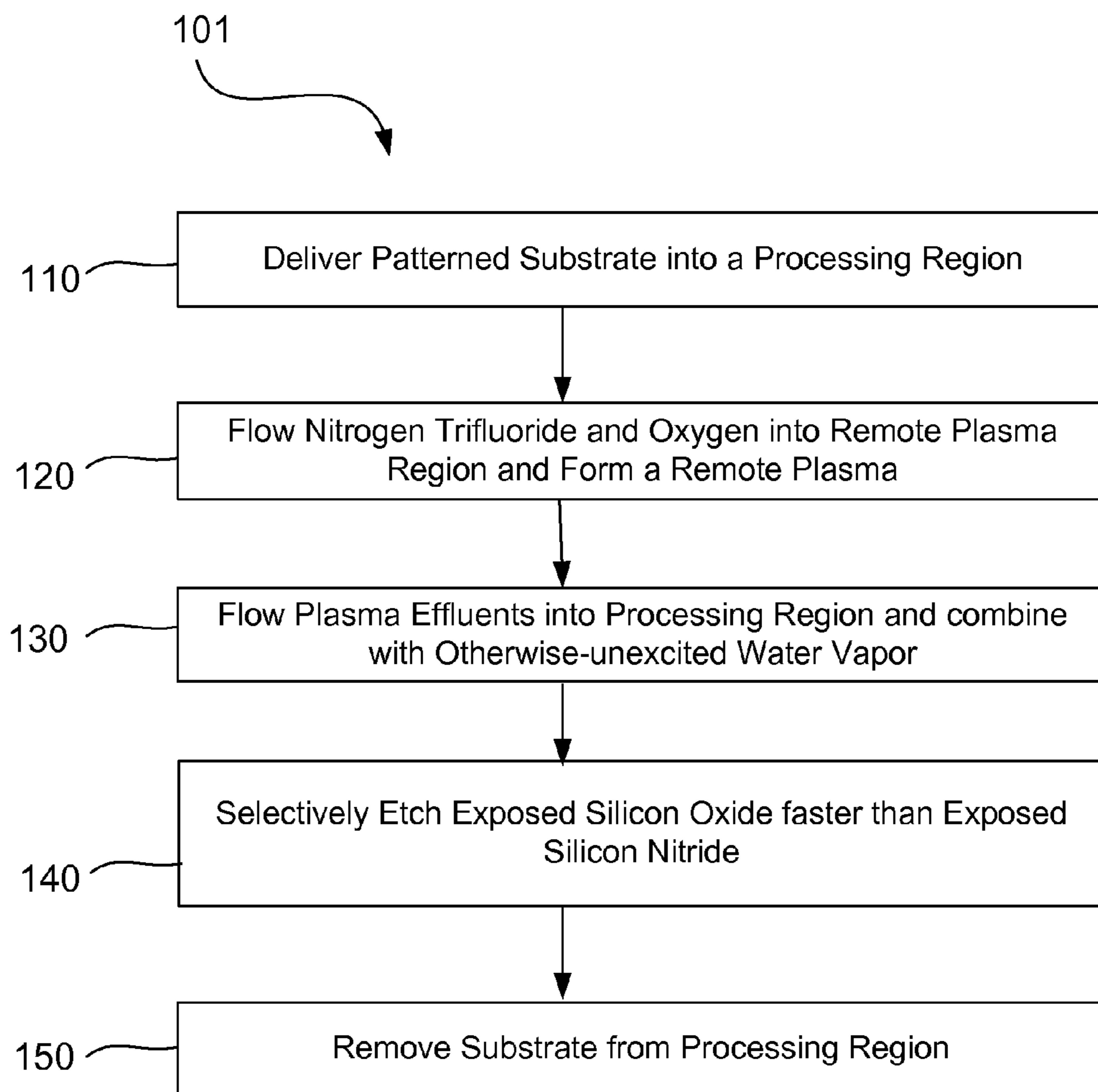


FIG. 1



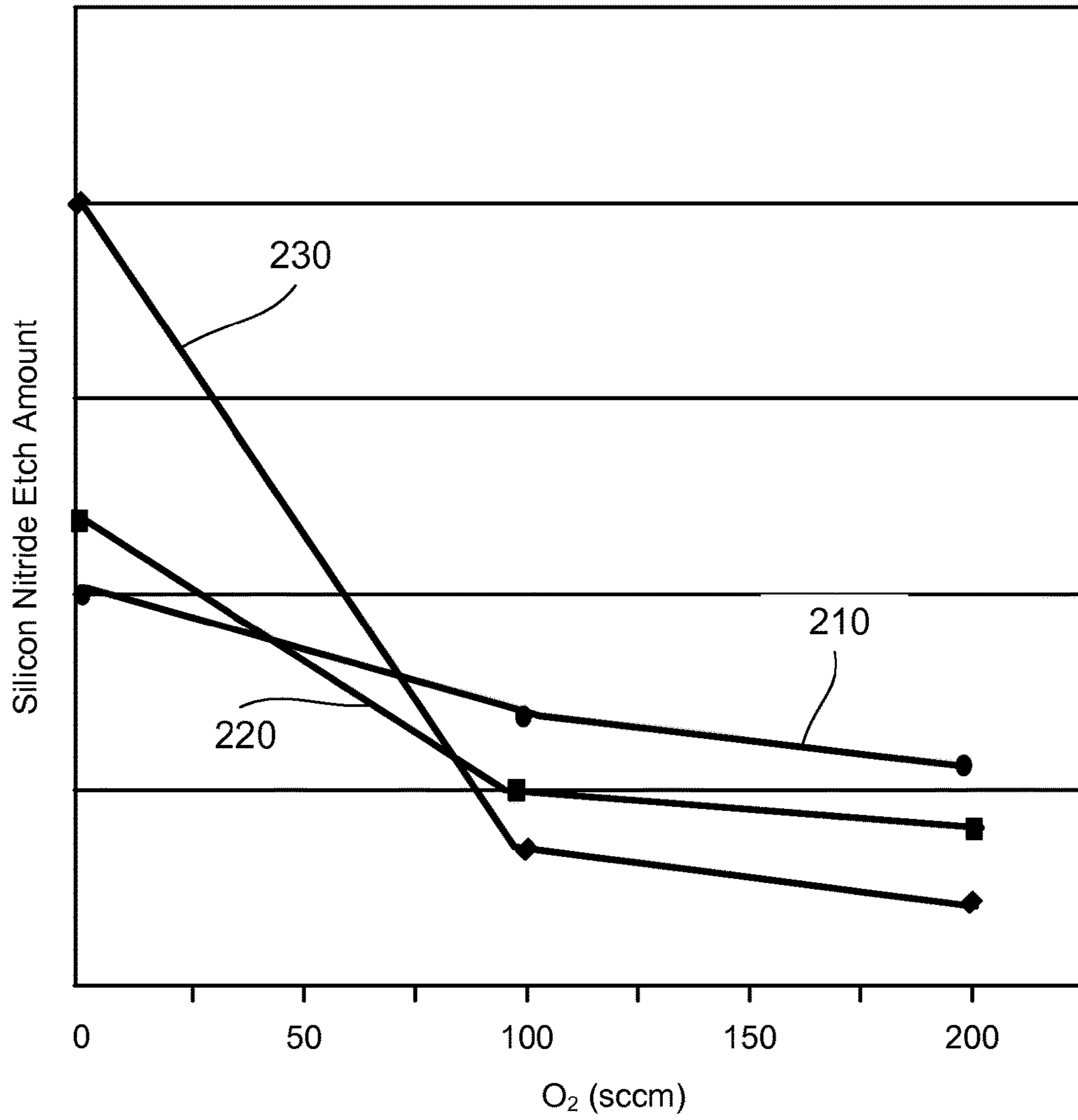
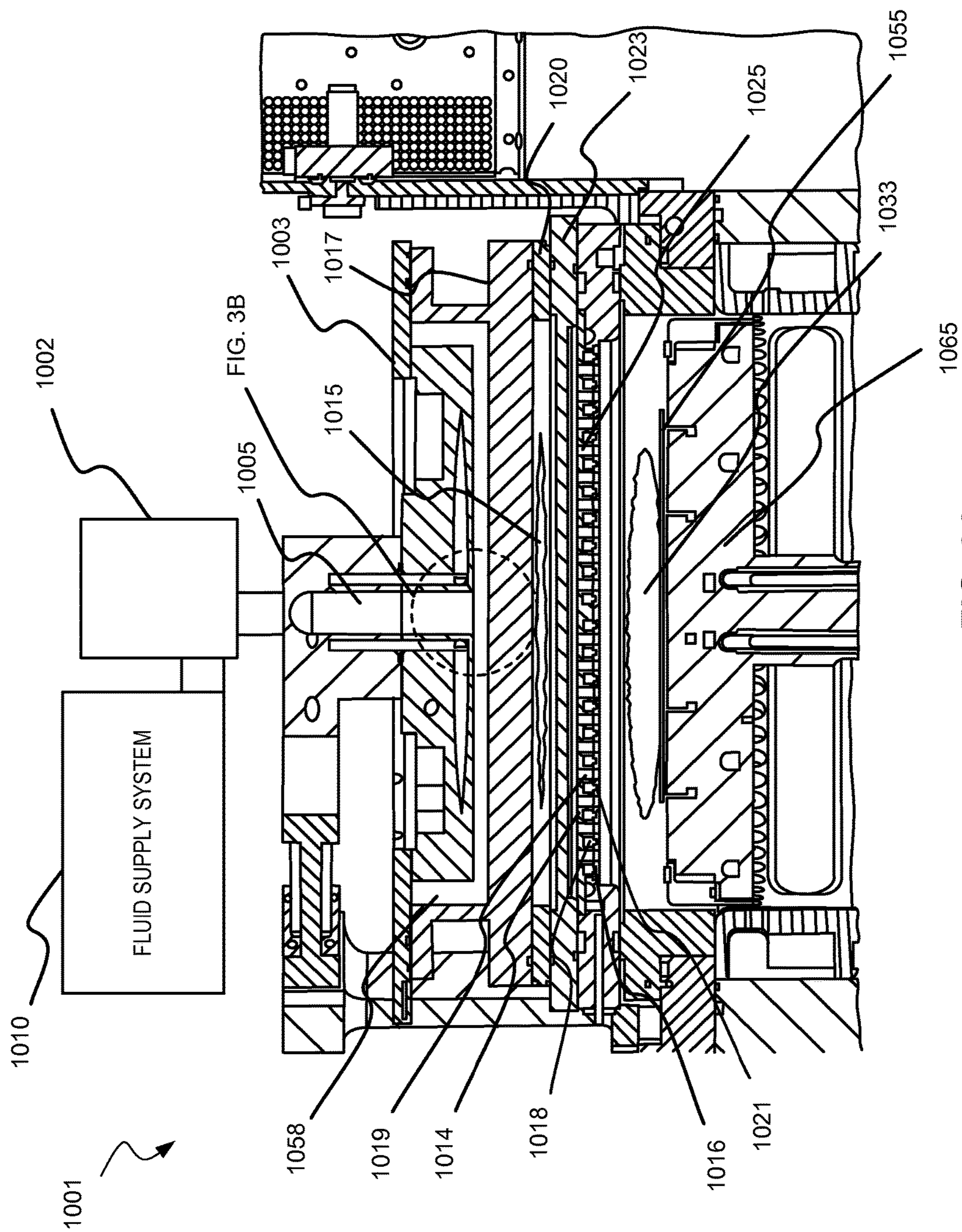


FIG. 2







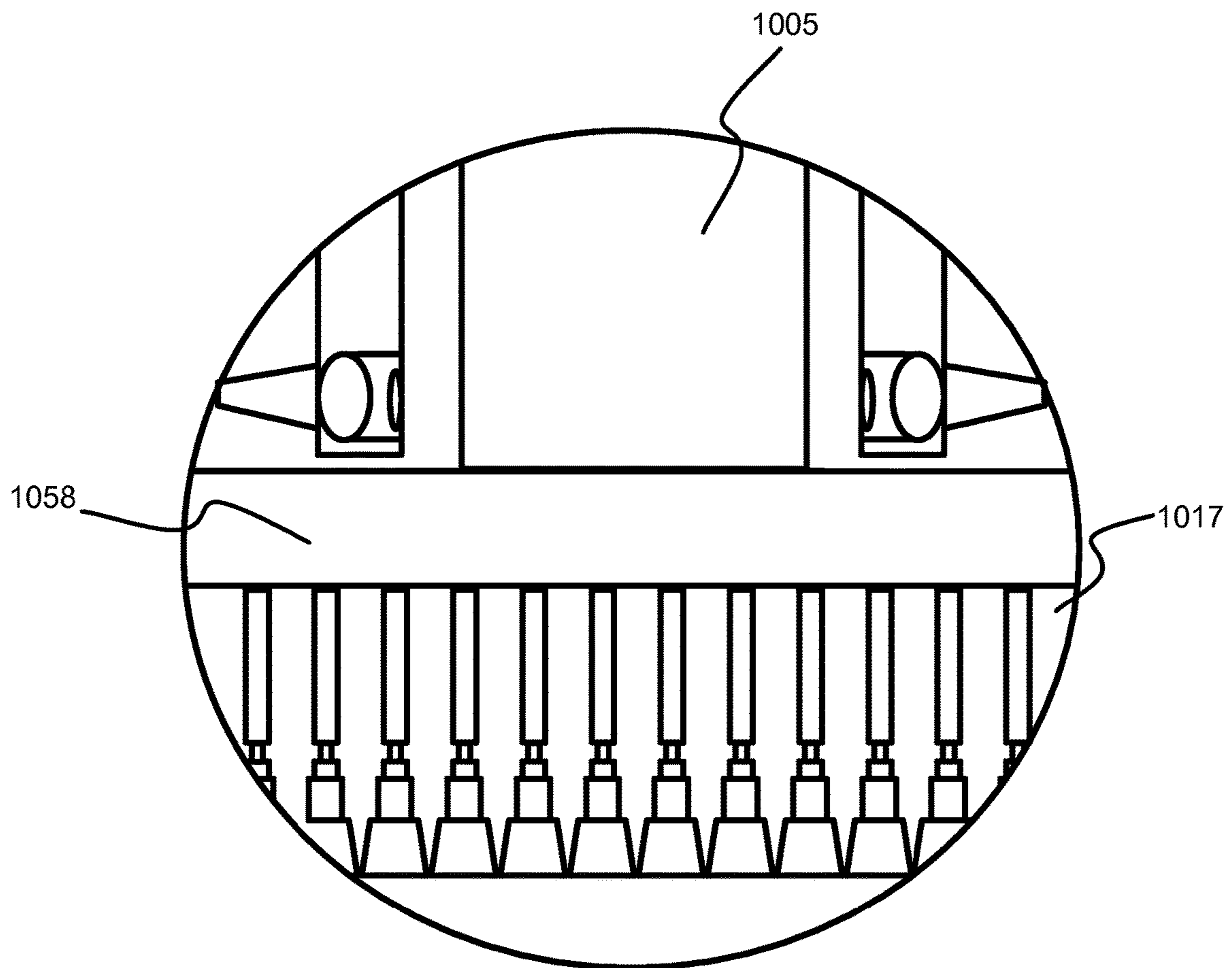


FIG. 3B



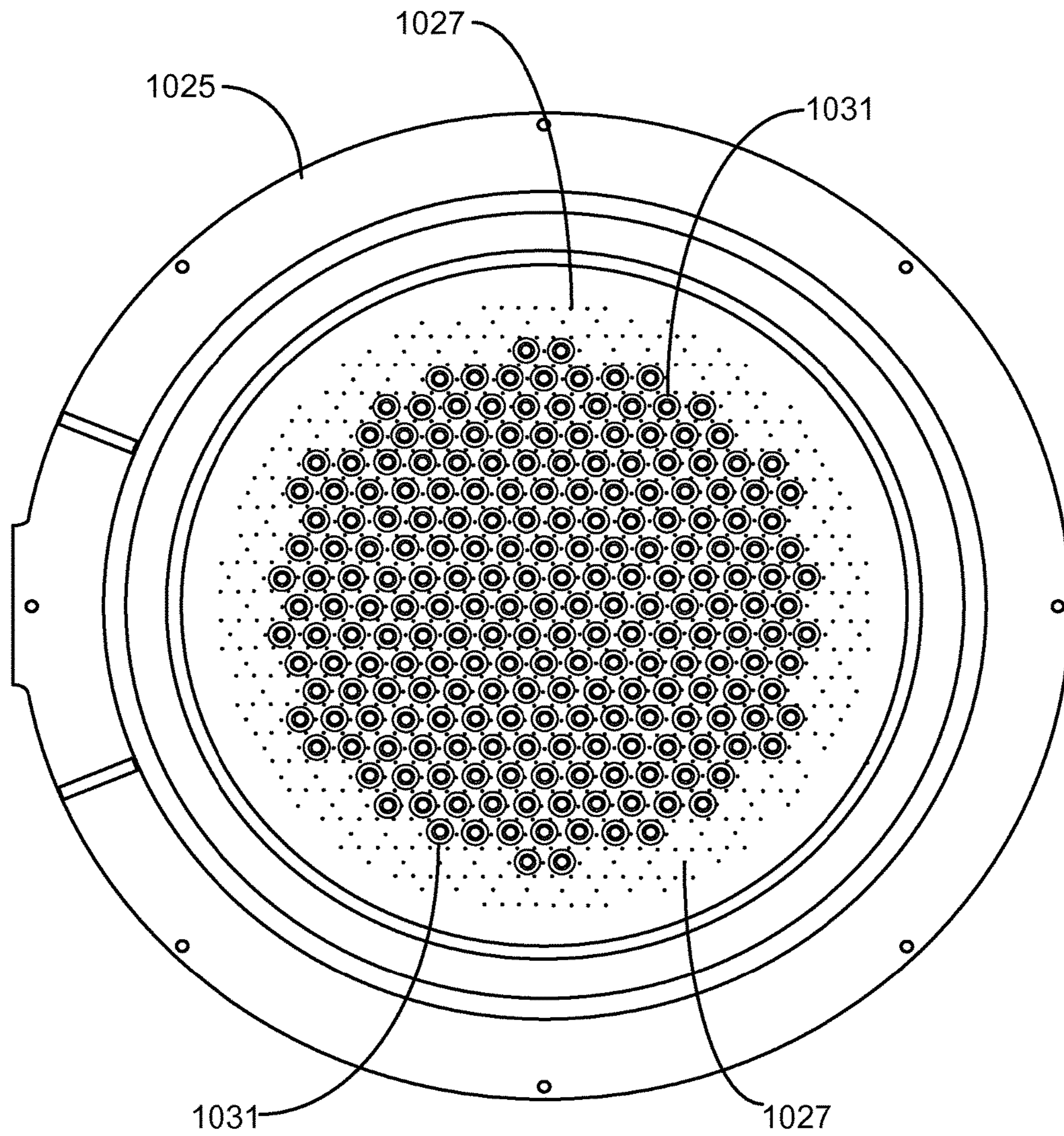


FIG. 3C



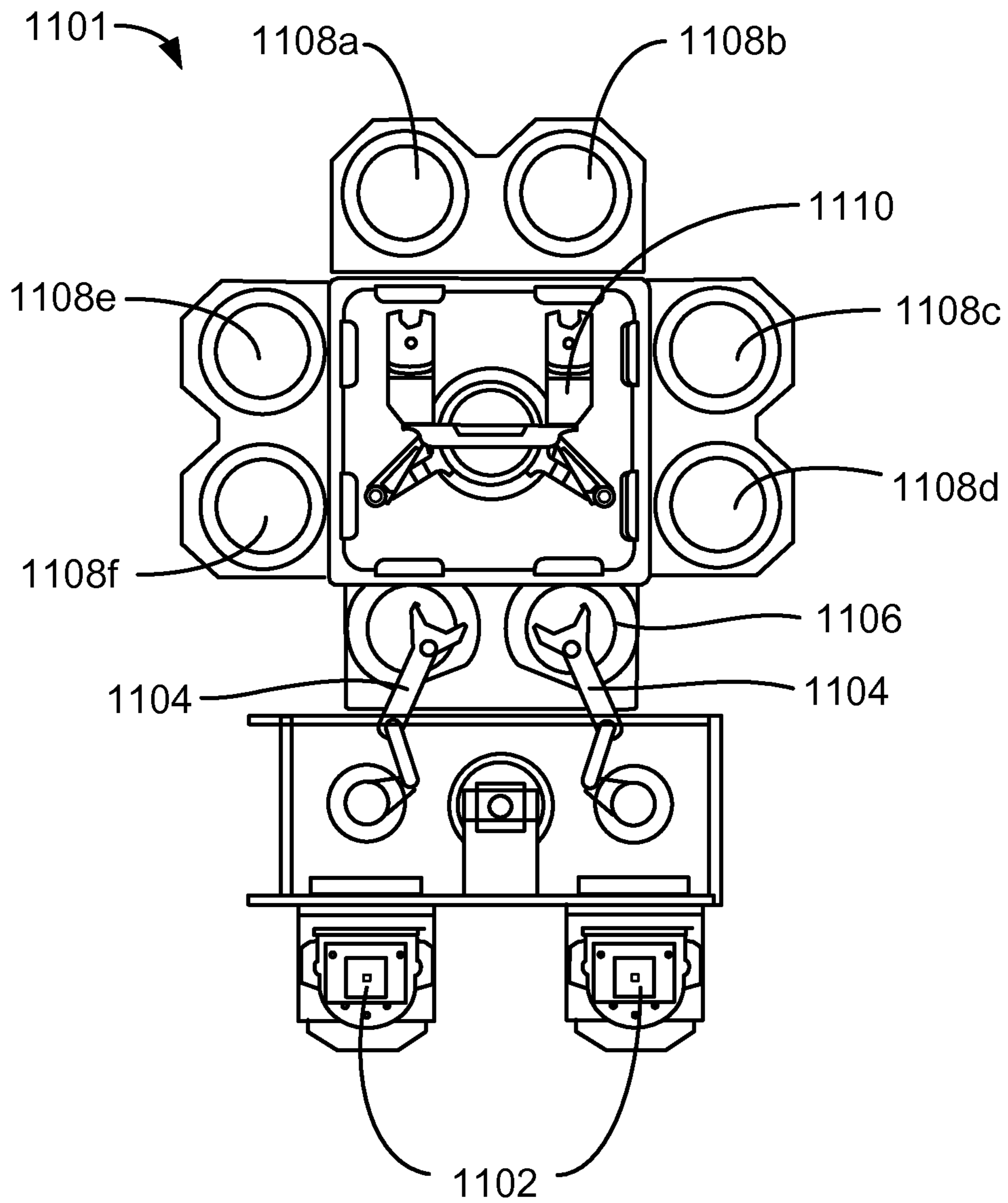


FIG. 4

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## OXIDE ETCH SELECTIVITY ENHANCEMENT

### CROSS-REFERENCES TO RELATED APPLICATIONS

This application claims the benefit of U.S. Prov. Pat. App. No. 62/055,587 filed Sep. 25, 2014, and titled "R3X WITH O2 ADDITION" by Chen et al., which is hereby incorporated herein in its entirety by reference for all purposes.

### FIELD

Embodiments of the invention relate to selectively etching silicon oxide.

### BACKGROUND

Integrated circuits are made possible by processes which produce intricately patterned material layers on substrate surfaces. Producing patterned material on a substrate requires controlled methods for removal of exposed material. Chemical etching is used for a variety of purposes including transferring a pattern in photoresist into underlying layers, thinning layers or thinning lateral dimensions of features already present on the surface. Often it is desirable to have an etch process which etches one material faster than another helping e.g. a pattern transfer process proceed. Such an etch process is said to be selective of the first material relative to the second material. As a result of the diversity of materials, circuits and processes, etch processes have been developed with a selectivity towards a variety of materials.

Dry etch processes are often desirable for selectively removing material from semiconductor substrates. The desirability stems from the ability to gently remove material from miniature structures with minimal physical disturbance. Dry etch processes also allow the etch rate to be abruptly stopped by removing the gas phase reagents. Some dry-etch processes involve the exposure of a substrate to remote plasma by-products formed from one or more precursors. For example, remote plasma excitation of ammonia and nitrogen trifluoride enables silicon oxide to be selectively removed from a patterned substrate when the plasma effluents are flowed into the substrate processing region.

Methods are needed to progressively expand this suite of selectivities in order to enable novel process flows.

### SUMMARY

A method of etching exposed silicon oxide on patterned heterogeneous structures is described and includes a gas phase etch using plasma effluents formed in a remote plasma. The remote plasma excites a fluorine-containing precursor in combination with an oxygen-containing precursor. Plasma effluents within the remote plasma are flowed into a substrate processing region where the plasma effluents combine with water vapor or an alcohol. The combination react with the patterned heterogeneous structures to remove an exposed silicon oxide portion faster than an exposed silicon nitride portion. The inclusion of the oxygen-containing precursor may suppress the silicon nitride etch rate and result in unprecedented silicon oxide etch selectivity.

Embodiments of the invention include methods of etching a patterned substrate. The methods include placing the patterned substrate in a substrate processing region of a substrate processing chamber. The patterned substrate has an exposed silicon oxide portion and an exposed silicon nitride

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portion. The methods further include flowing a radical-fluorine precursor into the substrate processing region. The methods further include flowing a radical-oxygen precursor into the substrate processing region. The methods further include flowing a hydrogen-and-oxygen-containing precursor into the substrate processing region without first passing the hydrogen-and-oxygen-containing precursor through any plasma. The hydrogen-and-oxygen-containing precursor comprises an OH group. The methods further include etching the exposed silicon oxide portion. The exposed silicon oxide portion etches at a first etch rate and the second exposed silicon oxide portion etches at a second etch rate which is lower than the first etch rate.

Embodiments of the invention include methods of etching a patterned substrate. The methods include placing the patterned substrate in a substrate processing region of a substrate processing chamber. The patterned substrate includes an exposed silicon oxide portion and an exposed silicon nitride portion. The methods further include flowing a fluorine-containing precursor and an oxygen-containing precursor into a remote plasma region fluidly coupled to the substrate processing region while forming a remote plasma in the remote plasma region to produce plasma effluents. The methods further include flowing a hydrogen-and-oxygen-containing precursor into the substrate processing region without first passing the hydrogen-and-oxygen-containing precursor through the remote plasma region. The hydrogen-and-oxygen-containing precursor comprises an O—H bond. The methods further include etching the exposed silicon oxide portion by flowing the plasma effluents into the substrate processing region. The exposed silicon oxide portion etches at a first etch rate and the exposed silicon nitride portion etches at a second etch rate which is lower than the first etch rate.

Embodiments of the invention include methods of etching a patterned substrate. The methods include placing the patterned substrate in a substrate processing region of a substrate processing chamber. The patterned substrate has an exposed silicon oxide portion and an exposed silicon nitride portion. The methods further include flowing nitrogen trifluoride and molecular oxygen into a remote plasma region fluidly coupled to the substrate processing region while forming a remote plasma in the remote plasma region to produce plasma effluents. The methods further include combining the plasma effluents with water vapor in the substrate processing region. The methods further include etching the exposed silicon oxide portion with the combination of the plasma effluents and the water vapor. The exposed silicon oxide portion etches at a first etch rate and the exposed silicon nitride portion etches at a second etch rate which is lower than the first etch rate.

Additional embodiments and features are set forth in part in the description that follows, and in part will become apparent to those skilled in the art upon examination of the specification or may be learned by the practice of the disclosed embodiments. The features and advantages of the disclosed embodiments may be realized and attained by means of the instrumentalities, combinations, and methods described in the specification.

### DESCRIPTION OF THE DRAWINGS

A further understanding of the nature and advantages of the embodiments may be realized by reference to the remaining portions of the specification and the drawings.

FIG. 1 is a flow chart of a silicon oxide selective etch process according to embodiments.



FIG. 2 is a plot of silicon nitride etch loss according to embodiments.

FIG. 3A shows a schematic cross-sectional view of a substrate processing chamber according to embodiments.

FIG. 3B shows a schematic cross-sectional view of a portion of a substrate processing chamber according to embodiments.

FIG. 3C shows a bottom view of a showerhead according to embodiments.

FIG. 4 shows a top view of an exemplary substrate processing system according to embodiments.

In the appended figures, similar components and/or features may have the same reference label. Further, various components of the same type may be distinguished by following the reference label by a dash and a second label that distinguishes among the similar components. If only the first reference label is used in the specification, the description is applicable to any one of the similar components having the same first reference label irrespective of the second reference label.

#### DETAILED DESCRIPTION

A method of etching exposed silicon oxide on patterned heterogeneous structures is described and includes a gas phase etch using plasma effluents formed in a remote plasma. The remote plasma excites a fluorine-containing precursor in combination with an oxygen-containing precursor. Plasma effluents within the remote plasma are flowed into a substrate processing region where the plasma effluents combine with water vapor or an alcohol. The combination react with the patterned heterogeneous structures to remove an exposed silicon oxide portion faster than an exposed silicon nitride portion. The inclusion of the oxygen-containing precursor may suppress the silicon nitride etch rate and result in unprecedented silicon oxide etch selectivity.

Selective remote gas phase etch processes have used a hydrogen-containing precursor of ammonia ( $\text{NH}_3$ ) and a fluorine-containing precursor of nitrogen trifluoride ( $\text{NF}_3$ ) which together flow through a remote plasma and into a substrate processing region. Alternative remote gas phase etch processes have also been developed which do not require ammonia. These remote gas phase etch processes remove oxide films much more rapidly than, e.g. silicon. However, even with the alternative processes, there is still a non-negligible loss of silicon nitride which is becoming a problem as linewidths decrease toward and below ten nanometers. The methods disclosed herein may exhibit a significantly greater etch rate selectivity of silicon oxide (regardless of dopants or deposition method) relative to silicon nitride.

In order to better understand and appreciate the invention, reference is now made to FIG. 1 which is a flow chart of a silicon oxide selective etch process **101** according to embodiments. Prior to the first operation, the substrate is patterned and an exposed silicon oxide portion is formed on the patterned substrate. An exposed silicon nitride portion is also formed on the patterned substrate. The patterned substrate is then placed within the substrate processing region in operation **110**.

Nitrogen trifluoride and molecular oxygen ( $\text{O}_2$ ) are flowed into a remote plasma region (operation **120**). The nitrogen trifluoride and oxygen are collectively excited in a remote plasma formed in the remote plasma region. The remote plasma system is positioned next to the substrate processing region and fluidly coupled through a showerhead. The remote plasma region may be within a distinct

module from the processing chamber and/or a compartment within the processing chamber. The plasma effluents formed in the remote plasma are then flowed into the substrate processing region (operation **130**). Water vapor is simultaneously flowed into the substrate processing region and combined with the plasma effluents. The water vapor is not passed through the remote plasma region and therefore may only be excited by interaction with the plasma effluents according to embodiments. The water vapor is not passed through any remote plasma region before entering the substrate processing region in embodiments.

Other sources of fluorine may be used to augment or replace the nitrogen trifluoride. In general, a fluorine-containing precursor is flowed into the plasma region and the fluorine-containing precursor comprises at least one precursor selected from the group consisting of atomic fluorine, diatomic fluorine, nitrogen trifluoride, carbon tetrafluoride, hydrogen fluoride and xenon difluoride in embodiments. Other sources of oxygen may be used to augment or replace the nitrogen trifluoride. In general, an oxygen-containing precursor is flowed into the plasma region and the fluorine-containing precursor comprises at least one precursor selected from the group consisting of molecular oxygen ( $\text{O}_2$ ), ozone ( $\text{O}_3$ ), dinitrogen oxide ( $\text{N}_2\text{O}$ ), hyponitrite ( $\text{N}_2\text{O}_2$ ) or nitrogen dioxide ( $\text{NO}_2$ ) in embodiments.

The patterned substrate is selectively etched (operation **140**) such that the exposed silicon oxide is removed at a higher rate than the exposed silicon nitride. The reactive chemical species are removed and the substrate is removed from the substrate processing region (operation **150**).

Reference is now made to FIG. 2 which is a plot of silicon nitride etch loss during silicon oxide etch processes including etch process **101** according to embodiments. The addition of the oxygen-containing precursor reduces the etch loss of silicon nitride regardless of whether the nitrogen trifluoride is flowed with a high flow rate (**210**), medium flow rate (**220**) or low flow rate (**210**). The low flow rate curve corresponds with a nitrogen trifluoride flow rate of 5 sccm. The medium flow rate and high flow rate curves correspond with 15 sccm and 25 sccm, respectively. At a low  $\text{NF}_3$  flow rate of 5 sccm, the loss of silicon nitride is highest of all three flow rates when no oxygen-containing precursor is included in the remote plasma region. Low  $\text{NF}_3$  flow rates are desirable for many applications to increase selectivity amongst different quality silicon oxide portions. As oxygen-containing precursor is introduced and its flow rate increased, the silicon nitride etch loss plummets in the case of the low nitrogen trifluoride flow rate such that the etch loss even drops below the medium and high flow rates. Combining the low flow rate of nitrogen trifluoride with a moderate flow of oxygen-containing precursor results in an unprecedented silicon oxide etch selectivity relative to silicon nitride.

The methods presented herein exhibit high etch selectivity of the exposed silicon oxide portion relative to an exposed silicon nitride portion. In operation **140**, the etch selectivity of the exposed silicon oxide portion relative to the exposed silicon nitride portion may be greater than 80:1, greater than 120:1 or greater than 150:1 according to embodiments. The etch rate of the exposed silicon oxide portion may be referred to as the first etch rate and the etch rate of the silicon nitride portion may be referred to herein as the second etch rate. The first etch rate may exceed the second etch rate by a factor of more than 80, more than 120 or more than 150 in embodiments. The observed selectivity (silicon oxide relative to silicon nitride) depends on the deposition technique, quality and dopant levels in the silicon oxide. In one



example the selectivity was observed to increase from 130 to 220 using the techniques presented herein for low quality sacrificial silicon oxide. Thus, the first etch rate may exceed the second etch rate by a factor of more than 150, more than 175 or more than 200 in some embodiments.

Cycling has been found to further increase the observed etch selectivities of silicon oxide relative to silicon nitride. Therefore, the unused reactants and other process effluents may be removed from the substrate processing region after operation 140 and before operation 150. Following process effluent removal, operations 120-140 or operations 130-140 may be repeated to remove additional silicon oxide from the exposed silicon oxide portion.

The gas phase etches described herein may not produce solid residue even at low substrate temperatures. Elimination of solid residue during the process avoids any potential disturbance of delicate features such as thin line structures. Elimination of solid residue also simplifies the process flows and decreases processing costs by removing a sublimation step. The fluorine-containing precursor, the remote plasma region and/or the oxygen-containing precursor are devoid of hydrogen during operation 140 in embodiments. The plasma effluents may also be devoid of hydrogen according to embodiments. Lack of hydrogen in the remote plasma region ensures minimal or no production of solid by-products on the patterned substrate.

In the examples presented herein, water was introduced through the showerhead into the substrate processing region without prior plasma excitation. Generally speaking, a hydrogen-and-oxygen-containing precursor may be introduced in place of or to augment the moisture. The hydrogen-and-oxygen-containing precursor may include an OH group in embodiments. The hydrogen-and-oxygen-containing precursor may be one of water or an alcohol according to embodiments. The alcohol may include one or more of methanol, ethanol and isopropyl alcohol in embodiments. The hydrogen-and-oxygen-containing-precursor may not pass through a remote plasma before entering the substrate processing region according to embodiments.

The pressure in the substrate processing region and the remote plasma region(s) during the etching operations may be between 0.1 Torr and 50 Torr, between 1 Torr and 15 Torr or between 5 Torr and 10 Torr in embodiments. The temperature of the patterned substrate during the etching operations may be between  $-20^{\circ}$  C. and  $250^{\circ}$  C., between  $0^{\circ}$  C. and  $50^{\circ}$  C. or between  $5^{\circ}$  C. and  $20^{\circ}$  C. in embodiments. Flow rate ranges are given in the course of describing exemplary equipment.

The method also includes applying power to the fluorine-containing precursor and the oxygen-containing precursor during operation 120 in the remote plasma regions to generate the plasma effluents. The plasma parameters described herein apply to remote plasmas used to etch the patterned substrate. As would be appreciated by one of ordinary skill in the art, the plasma may include a number of charged and neutral species including radicals and ions. The plasma may be generated using known techniques (e.g., RF, capacitively coupled, inductively coupled). In an embodiment, the remote plasma power may be applied to the remote plasma region at a level between 500 W and 10 kW for a remote plasma external to the substrate processing chamber. The remote plasma power may be applied using inductive coils, in embodiments, in which case the remote plasma will be referred to as an inductively-coupled plasma (ICP) or may be applied using capacitive plates, in which case the remote plasma will be referred to as a capacitive-coupled plasma (CCP). According to embodiments, the remote

plasma power may be applied to the remote plasma region at a level between 25 watts and 500 watts for a remote plasma within the substrate processing chamber. Other possible plasma parameters and ranges will be described along with exemplary equipment herein.

For both treatment remote plasmas and etch remote plasmas, the flows of the precursors into the remote plasma region may further include one or more relatively inert gases such as He, N<sub>2</sub>, Ar. The inert gas can be used to improve plasma stability, ease plasma initiation, and improve process uniformity. Argon may be helpful, as an additive, to promote the formation of a stable plasma. Process uniformity is generally increased when helium is included. These additives are present in embodiments throughout this specification. Flow rates and ratios of the different gases may be used to control etch rates and etch selectivity.

In embodiments, an ion suppressor (which may be the showerhead) may be used to provide radical and/or neutral species for gas-phase etching. The ion suppressor may also be referred to as an ion suppression element. In embodiments, for example, the ion suppressor is used to filter etching plasma effluents en route from the remote plasma region to the substrate processing region. The ion suppressor may be used to provide a reactive gas having a higher concentration of radicals than ions. Plasma effluents pass through the ion suppressor disposed between the remote plasma region and the substrate processing region. The ion suppressor functions to dramatically reduce or substantially eliminate ionic species traveling from the plasma generation region to the substrate. The ion suppressors described herein are simply one way to achieve a low electron temperature in the substrate processing region during the gas-phase etch processes described herein.

In embodiments, an electron beam is passed through the substrate processing region in a plane parallel to the substrate to reduce the electron temperature of the plasma effluents. A simpler showerhead may be used if an electron beam is applied in this manner. The electron beam may be passed as a laminar sheet disposed above the substrate in embodiments. The electron beam provides a source of neutralizing negative charge and provides a more active means for reducing the flow of positively charged ions towards the substrate and increasing the etch selectivity in embodiments. The flow of plasma effluents and various parameters governing the operation of the electron beam may be adjusted to lower the electron temperature measured in the substrate processing region.

The electron temperature may be measured using a Langmuir probe in the substrate processing region during excitation of a plasma in the remote plasma. In aluminum removal embodiments, the electron temperature may be less than 0.5 eV, less than 0.45 eV, less than 0.4 eV, or less than 0.35 eV. These extremely low values for the electron temperature are enabled by the presence of the electron beam, showerhead and/or the ion suppressor. Uncharged neutral and radical species may pass through the electron beam and/or the openings in the ion suppressor to react at the substrate. Such a process using radicals and other neutral species can reduce plasma damage compared to conventional plasma etch processes that include sputtering and bombardment. Embodiments of the present invention are also advantageous over conventional wet etch processes where surface tension of liquids can cause bending and peeling of small features. In point of contrast, the electron temperature during the aluminum oxide removal process may be greater than 0.5 eV, greater than 0.6 eV or greater than 0.7 eV according to embodiments.



The substrate processing region may be described herein as “plasma-free” during the etch processes described herein. “Plasma-free” does not necessarily mean the region is devoid of plasma. Ionized species and free electrons created within the plasma region may travel through pores (apertures) in the partition (showerhead) at exceedingly small concentrations. The borders of the plasma in the chamber plasma region may encroach to some small degree upon the substrate processing region through the apertures in the showerhead. Furthermore, a low intensity plasma may be created in the substrate processing region without eliminating desirable features of the etch processes described herein. All causes for a plasma having much lower intensity ion density than the chamber plasma region during the creation of the excited plasma effluents do not deviate from the scope of “plasma-free” as used herein.

FIG. 3A shows a cross-sectional view of an exemplary substrate processing chamber **1001** with a partitioned plasma generation region within the processing chamber. During film etching, a process gas may be flowed into chamber plasma region **1015** through a gas inlet assembly **1005**. A remote plasma system (RPS) **1002** may optionally be included in the system, and may process a first gas which then travels through gas inlet assembly **1005**. The process gas may be excited within RPS **1002** prior to entering chamber plasma region **1015**. Accordingly, the fluorine-containing precursor as discussed above, for example, may pass through RPS **1002** or bypass the RPS unit in embodiments.

A cooling plate **1003**, faceplate **1017**, ion suppressor **1023**, showerhead **1025**, and a substrate support **1065** (also known as a pedestal), having a substrate **1055** disposed thereon, are shown and may each be included according to embodiments. Pedestal **1065** may have a heat exchange channel through which a heat exchange fluid flows to control the temperature of the substrate. This configuration may allow the substrate **1055** temperature to be cooled or heated to maintain relatively low temperatures, such as between  $-20^{\circ}$  C. to  $200^{\circ}$  C. Pedestal **1065** may also be resistively heated to relatively high temperatures, such as between  $100^{\circ}$  C. and  $1100^{\circ}$  C., using an embedded heater element.

Exemplary configurations may include having the gas inlet assembly **1005** open into a gas supply region **1058** partitioned from the chamber plasma region **1015** by faceplate **1017** so that the gases/species flow through the holes in the faceplate **1017** into the chamber plasma region **1015**. Structural and operational features may be selected to prevent significant backflow of plasma from the chamber plasma region **1015** back into the supply region **1058**, gas inlet assembly **1005**, and fluid supply system **1010**. The structural features may include the selection of dimensions and cross-sectional geometries of the apertures in faceplate **1017** to deactivate back-streaming plasma. The operational features may include maintaining a pressure difference between the gas supply region **1058** and chamber plasma region **1015** that maintains a unidirectional flow of plasma through the showerhead **1025**. The faceplate **1017**, or a conductive top portion of the chamber, and showerhead **1025** are shown with an insulating ring **1020** located between the features, which allows an AC potential to be applied to the faceplate **1017** relative to showerhead **1025** and/or ion suppressor **1023**. The insulating ring **1020** may be positioned between the faceplate **1017** and the showerhead **1025** and/or ion suppressor **1023** enabling a capacitively coupled plasma (CCP) to be formed in the chamber plasma region.

The plurality of holes in the ion suppressor **1023** may be configured to control the passage of the activated gas, i.e., the ionic, radical, and/or neutral species, through the ion suppressor **1023**. For example, the aspect ratio of the holes, or the hole diameter to length, and/or the geometry of the holes may be controlled so that the flow of ionically-charged species in the activated gas passing through the ion suppressor **1023** is reduced. The holes in the ion suppressor **1023** may include a tapered portion that faces chamber plasma region **1015**, and a cylindrical portion that faces the showerhead **1025**. The cylindrical portion may be shaped and dimensioned to control the flow of ionic species passing to the showerhead **1025**. An adjustable electrical bias may also be applied to the ion suppressor **1023** as an additional means to control the flow of ionic species through the suppressor. The ion suppression element **1023** may function to reduce or eliminate the amount of ionically charged species traveling from the plasma generation region to the substrate. Uncharged neutral and radical species may still pass through the openings in the ion suppressor to react with the substrate.

Plasma power can be of a variety of frequencies or a combination of multiple frequencies. In the exemplary processing system the plasma may be provided by RF power delivered to faceplate **1017** relative to ion suppressor **1023** and/or showerhead **1025**. The RF power may be between about 10 watts and about 5000 watts, between about 100 watts and about 2000 watts, between about 200 watts and about 1500 watts, or between about 200 watts and about 1000 watts in embodiments. The RF frequency applied in the exemplary processing system may be low RF frequencies less than about 200 kHz, high RF frequencies between about 10 MHz and about 15 MHz, or microwave frequencies greater than or about 1 GHz in embodiments. The plasma power may be capacitively-coupled (CCP) or inductively-coupled (ICP) into the remote plasma region.

A precursor, for example a fluorine-containing precursor and an oxygen-containing precursor, may be flowed into substrate processing region **1033** by embodiments of the showerhead described herein. Excited species derived from the process gas in chamber plasma region **1015** may travel through apertures in the ion suppressor **1023**, and/or showerhead **1025** and react with an additional precursor flowing into substrate processing region **1033** from a separate portion of the showerhead. Alternatively, if all precursor species are being excited in chamber plasma region **1015**, no additional precursors may be flowed through the separate portion of the showerhead. Little or no plasma may be present in substrate processing region **1033** during the remote plasma etch process. Excited derivatives of the precursors may combine in the region above the substrate and/or on the substrate to etch structures or remove species from the substrate.

The processing gases may be excited in chamber plasma region **1015** and may be passed through the showerhead **1025** to substrate processing region **1033** in the excited state. While a plasma may be generated in substrate processing region **1033**, a plasma may alternatively not be generated in the processing region. In one example, the only excitation of the processing gas or precursors may be from exciting the processing gases in chamber plasma region **1015** to react with one another in substrate processing region **1033**. As previously discussed, this may be to protect the structures patterned on substrate **1055**.

FIG. 3B shows a detailed view of the features affecting the processing gas distribution through faceplate **1017**. The gas distribution assemblies such as showerhead **1025** for use



in the processing chamber section **1001** may be referred to as dual channel showerheads (DCSH) and are additionally detailed in the embodiments described in FIG. 3A as well as FIG. 3C herein. The dual channel showerhead may provide for etching processes that allow for separation of etchants outside of the processing region **1033** to provide limited interaction with chamber components and each other prior to being delivered into the processing region.

The showerhead **1025** may comprise an upper plate **1014** and a lower plate **1016**. The plates may be coupled with one another to define a volume **1018** between the plates. The coupling of the plates may be so as to provide first fluid channels **1019** through the upper and lower plates, and second fluid channels **1021** through the lower plate **1016**. The formed channels may be configured to provide fluid access from the volume **1018** through the lower plate **1016** via second fluid channels **1021** alone, and the first fluid channels **1019** may be fluidly isolated from the volume **1018** between the plates and the second fluid channels **1021**. The volume **1018** may be fluidly accessible through a side of the gas distribution assembly **1025**. Although the exemplary system of FIGS. 3A-3C includes a dual-channel showerhead, it is understood that alternative distribution assemblies may be utilized that maintain first and second precursors fluidly isolated prior to substrate processing region **1033**. For example, a perforated plate and tubes underneath the plate may be utilized, although other configurations may operate with reduced efficiency or not provide as uniform processing as the dual-channel showerhead described.

In the embodiment shown, showerhead **1025** may distribute via first fluid channels **1019** process gases which contain plasma effluents upon excitation by a plasma in chamber plasma region **1015**. In embodiments, the process gas introduced into RPS **1002** and/or chamber plasma region **1015** may contain fluorine, e.g.,  $\text{NF}_3$ . The process gas may also include a carrier gas such as helium, argon, nitrogen ( $\text{N}_2$ ), etc. Plasma effluents may include ionized or neutral derivatives of the process gas and may also be referred to herein as a radical-fluorine precursor referring to the atomic constituent of the process gas introduced.

FIG. 3C is a bottom view of a showerhead **1025** for use with a processing chamber in embodiments. Showerhead **1025** corresponds with the showerhead shown in FIG. 3A. Through-holes **1031**, which show a view of first fluid channels **1019**, may have a plurality of shapes and configurations to control and affect the flow of precursors through the showerhead **1025**. Small holes **1027**, which show a view of second fluid channels **1021**, may be distributed substantially evenly over the surface of the showerhead, even amongst the through-holes **1031**, which may help to provide more even mixing of the precursors as they exit the showerhead than other configurations.

The chamber plasma region **1015** or a region in an RPS may be referred to as a remote plasma region. In embodiments, the radical-fluorine precursor and the radical-oxygen precursor are created in the remote plasma region and travel into the substrate processing region to combine with the hydrogen-and-oxygen-containing precursor. In embodiments, the hydrogen-and-oxygen-containing precursor is excited only by the radical-fluorine precursor and the radical-oxygen precursor. Plasma power may essentially be applied only to the remote plasma region in embodiments to ensure that the radical-fluorine precursor and the radical-oxygen precursor provide the dominant excitation.

Embodiments of the dry etch systems may be incorporated into larger fabrication systems for producing integrated circuit chips. FIG. 4 shows one such processing system

(mainframe) **1101** of deposition, etching, baking, and curing chambers in embodiments. In the figure, a pair of front opening unified pods (load lock chambers **1102**) supply substrates of a variety of sizes that are received by robotic arms **1104** and placed into a low pressure holding area **1106** before being placed into one of the substrate processing chambers **1108a-f**. A second robotic arm **1110** may be used to transport the substrate wafers from the holding area **1106** to the substrate processing chambers **1108a-f** and back. Each substrate processing chamber **1108a-f**, can be outfitted to perform a number of substrate processing operations including the dry etch processes described herein in addition to cyclical layer deposition (CLD), atomic layer deposition (ALD), chemical vapor deposition (CVD), physical vapor deposition (PVD), etch, pre-clean, degas, orientation, and other substrate processes.

Nitrogen trifluoride (or another fluorine-containing precursor) may be flowed into chamber plasma region **1020** at rates between about 1 sccm and about 40 sccm, between about 3 sccm and about 25 sccm or between about 5 sccm and about 10 sccm in embodiments. Oxygen (or another oxygen-containing precursor) may be flowed into chamber plasma region **1020** at rates between about 10 sccm and about 400 sccm, between about 30 sccm and about 250 sccm or between about 50 sccm and about 150 sccm in embodiments. Water vapor may be flowed into substrate processing region **1070** at rates between about 5 sccm and about 100 sccm, between about 10 sccm and about 50 sccm or between about 15 sccm and about 25 sccm according to embodiments. The flow rate ratio of the oxygen-containing precursor to the fluorine-containing precursor may be greater than 4, greater than 6 or greater than 10 according to embodiments. The flow rate ratio of the oxygen-containing precursor to the fluorine-containing precursor may be less than 40, less than 30 or less than 20 in embodiments. Upper limits may be combined with lower limits according to embodiments.

The showerhead may be referred to as a dual-channel showerhead as a result of the two distinct pathways into the substrate processing region. The fluorine-containing precursor and the oxygen-containing precursor may be flowed through the through-holes in the dual-zone showerhead and the water vapor may pass through separate zones in the dual-zone showerhead. The separate zones may open into the substrate processing region but not into the remote plasma region as described above.

Combined flow rates of water vapor and plasma effluents into the substrate processing region may account for 0.05% to about 20% by volume of the overall gas mixture; the remainder being carrier gases. The fluorine-containing precursor and the oxygen-containing precursor flowed into the remote plasma region but the plasma effluents has the same volumetric flow ratio, in embodiments. In the case of the fluorine-containing precursor, a purge or carrier gas may be first initiated into the remote plasma region before those of the fluorine-containing gas and the oxygen-containing precursor to stabilize the pressure within the remote plasma region.

As used herein "substrate" may be a support substrate with or without layers formed thereon. The patterned substrate may be an insulator or a semiconductor of a variety of doping concentrations and profiles and may, for example, be a semiconductor substrate of the type used in the manufacture of integrated circuits. Exposed "silicon oxide" of the patterned substrate is predominantly  $\text{SiO}_2$  but may include concentrations of other elemental constituents such as, e.g., nitrogen, hydrogen and carbon. In some embodiments, sili-



con oxide portions etched using the methods disclosed herein consist essentially of silicon and oxygen. Exposed “silicon nitride” of the patterned substrate is predominantly  $\text{Si}_3\text{N}_4$  but may include concentrations of other elemental constituents such as, e.g., oxygen, hydrogen and carbon. In some embodiments, silicon nitride portions described herein consist essentially of silicon and nitrogen.

The terms “gap” and “trench” are used throughout with no implication that the etched geometry has a large horizontal aspect ratio. Viewed from above the surface, trenches may appear circular, oval, polygonal, rectangular, or a variety of other shapes. A trench may be in the shape of a moat around an island of material. The term “via” is used to refer to a low aspect ratio trench (as viewed from above) which may or may not be filled with metal to form a vertical electrical connection. As used herein, a conformal etch process refers to a generally uniform removal of material on a surface in the same shape as the surface, i.e., the surface of the etched layer and the pre-etch surface are generally parallel. A person having ordinary skill in the art will recognize that the etched interface likely cannot be 100% conformal and thus the term “generally” allows for acceptable tolerances.

The term “precursor” is used to refer to any process gas which takes part in a reaction to either remove material from or deposit material onto a surface. “Plasma effluents” describe gas exiting from the chamber plasma region and entering the substrate processing region. Plasma effluents are in an “excited state” wherein at least some of the gas molecules are in vibrationally-excited, dissociated and/or ionized states. A “radical precursor” is used to describe plasma effluents (a gas in an excited state which is exiting a plasma) which participate in a reaction to either remove material from or deposit material on a surface. “Radical-fluorine precursors” describe radical precursors which contain fluorine but may contain other elemental constituents. “Radical-oxygen precursors” describe radical precursors which contain oxygen but may contain other elemental constituents. The phrase “inert gas” refers to any gas which does not form chemical bonds when etching or being incorporated into a film. Exemplary inert gases include noble gases but may include other gases so long as no chemical bonds are formed when (typically) trace amounts are trapped in a film.

Having disclosed several embodiments, it will be recognized by those of skill in the art that various modifications, alternative constructions, and equivalents may be used without departing from the spirit of the disclosed embodiments. Additionally, a number of well-known processes and elements have not been described in order to avoid unnecessarily obscuring the present invention. Accordingly, the above description should not be taken as limiting the scope of the invention.

Where a range of values is provided, it is understood that each intervening value, to the tenth of the unit of the lower limit unless the context clearly dictates otherwise, between the upper and lower limits of that range is also specifically disclosed. Each smaller range between any stated value or intervening value in a stated range and any other stated or intervening value in that stated range is encompassed. The upper and lower limits of these smaller ranges may independently be included or excluded in the range, and each range where either, neither or both limits are included in the smaller ranges is also encompassed within the invention, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included.

As used herein and in the appended claims, the singular forms “a”, “an”, and “the” include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to “a process” includes a plurality of such processes and reference to “the dielectric material” includes reference to one or more dielectric materials and equivalents thereof known to those skilled in the art, and so forth.

Also, the words “comprise,” “comprising,” “include,” “including,” and “includes” when used in this specification and in the following claims are intended to specify the presence of stated features, integers, components, or steps, but they do not preclude the presence or addition of one or more other features, integers, components, steps, acts, or groups.

The invention claimed is:

1. A method of etching a patterned substrate, the method comprising:

placing the patterned substrate in a substrate processing region of a substrate processing chamber, wherein the patterned substrate comprises an exposed silicon oxide portion and an exposed silicon nitride portion;

flowing a fluorine-containing precursor and an oxygen-containing precursor into a remote plasma region fluidly coupled to the substrate processing region while forming a remote plasma in the remote plasma region to produce plasma effluents;

flowing a hydrogen-and-oxygen-containing precursor into the substrate processing region without first passing the hydrogen-and-oxygen-containing precursor through the remote plasma region, wherein the hydrogen-and-oxygen-containing precursor comprises an O—H bond; and

etching the exposed silicon oxide portion by flowing the plasma effluents into the substrate processing region, wherein the exposed silicon oxide portion etches at a first etch rate and the exposed silicon nitride portion etches at a second etch rate which is lower than the first etch rate.

2. The method of claim 1 wherein the first etch rate exceeds the second etch rate by a factor of about 80 or more.

3. The method of claim 1 wherein the substrate processing region is plasma-free during the operation of etching the exposed silicon oxide portion.

4. The method of claim 1 wherein the hydrogen-and-oxygen-containing precursor is not excited by any plasma outside the substrate processing region prior to entering the substrate processing region.

5. The method of claim 1 wherein the fluorine-containing precursor comprises a precursor selected from the group consisting of atomic fluorine, diatomic fluorine, nitrogen trifluoride, carbon tetrafluoride, hydrogen fluoride and xenon difluoride.

6. The method of claim 1 wherein the remote plasma region, the substrate processing region, the fluorine-containing precursor, the oxygen-containing precursor and the plasma effluents are essentially devoid of hydrogen during the operation of etching the exposed silicon oxide portion.

7. The method of claim 1 wherein the fluorine-containing precursor and the oxygen-containing precursor flow through through-holes in a dual-zone showerhead and the hydrogen-and-oxygen-containing precursor passes through separate zones in the dual-zone showerhead, wherein the separate zones open into the substrate processing region but not directly into the remote plasma region.

8. The method of claim 1 wherein the hydrogen-and-oxygen-containing precursor comprises one of water vapor or an alcohol.

9. The method of claim 1 wherein the oxygen-containing precursor comprises one or more of O<sub>2</sub>, O<sub>3</sub>, N<sub>2</sub>O, NO<sub>2</sub> and N<sub>2</sub>O<sub>2</sub>.

10. A method of etching a patterned substrate, the method comprising:

placing the patterned substrate in a substrate processing region of a substrate processing chamber, wherein the patterned substrate comprises an exposed silicon oxide portion and an exposed silicon nitride portion;

flowing nitrogen trifluoride and molecular oxygen into a remote plasma region fluidly coupled to the substrate processing region while forming a remote plasma in the remote plasma region to produce plasma effluents;

combining the plasma effluents with water vapor in the substrate processing region; and

etching the exposed silicon oxide portion with the combination of the plasma effluents and the water vapor, wherein the exposed silicon oxide portion etches at a first etch rate and the exposed silicon nitride portion etches at a second etch rate which is lower than the first etch rate.

11. The method of claim 10 wherein the water vapor is flowed into the remote plasma region without first passing through the remote plasma region.

12. The method of claim 10 wherein the first etch rate exceeds the second etch rate by a factor of about 120 or more.

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